Market Structure and Monetary Non-neutrality*

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Abstract

Canonical macroeconomic models of pricing under nominal rigidities assume markets consist of atomistic firms. Most US retail markets are dominated by a few large firms. To bridge this gap, I extend an equilibrium menu cost model to allow for a continuum of sectors with two large firms in each sector. Compared to a model with monopolistically competitive markets, and calibrated to the same good-level data on price adjustment, the duopoly model generates output responses to monetary shocks that are more than twice as large. Firm-level prices respond equally to idiosyncratic shocks, but less to aggregate shocks in the calibrated duopoly model. Under duopoly, the response of low priced firms to an increase in money is dampened: a falling real price at its competitor weakens both the incentive to increase prices, and price conditional on adjustment. The dynamic duopoly model also implies (i) large first order welfare losses from nominal rigidities, (ii) lower menu costs, (iii) a U-shaped relationship between market concentration and price flexibility, for which I find strong evidence in the data, (iv) a source of downward bias in markup estimates attained from inverting a static oligopoly model.

Keywords: Oligopoly, menu costs, monetary policy, firm dynamics.

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1 Introduction

In macroeconomic models a standard assumption made for tractability is that firms behave competitively in the markets in which they sell their goods. This paper relaxes this assumption in the context of a monetary business cycle model in which firms face nominal rigidity. I explore an oligopolistic market structure—familiar from other areas of economics—in which firms are large and markets are imperfectly competitive. Aggregating an economy of oligopolistic sectors, I find a range of new results relative to the monopolistically competitive benchmark. In particular, the real effects of shocks are substantially larger under oligopoly.

Figure 1 provides a simple motivation for this paper: product markets are highly concentrated. This is not a new fact. But Figure 1 documents this for a broad range of narrowly defined markets. Defining a market by a product category (e.g. ketchup, mayonnaise) in a specific state and quarter, I construct measures of concentration using weekly price and quantity data from the IRI data.[1] The median number of firms in a market is 37, while the effective number of firms—a measure of market concentration defined by the inverse Herfindahl index—has a median of around three, and the median revenue share of the two largest firms is just under 70 percent.[2] The number of firms in markets may be large, but firms are not equally sized and most sales accrue to only a few firms. This paper investigates the macroeconomic implications of oligopolistic markets which seem appropriate given these facts, and have been studied previously in a microeconomic context.

To allow for such strategic interaction I extend a menu cost model of price adjustment to accommodate a dynamic duopoly within each sector. Firms face persistent, idiosyncratic shocks to demand and must pay a fixed cost to change the price of good they produce. To study the implications of this model for monetary policy I aggregate a continuum of such sectors and subject the economy to aggregate shocks to the money supply.

I compare the quantitative outcomes from this model to its counterpart in which markets

[1] The IRI data is weekly good level data for the universe of goods in a panel of over 5,000 supermarkets in the US from 2001 to 2011. For more details on the IRI data and its treatment in this paper see Appendix A.

[2] The inverse Herfindahl index (IHI) admits an interpretation of 'effective number of firms' as follows. The IHI of a sector with n equally sized firms is n. Therefore if a sector has an IHI of 2.4, then it has a Herfindahl index consistent with a market populated by between 2 and 3 equally sized firms. For more on this interpretation see Adelman (1969). For a recent paper that uses this measure of market concentration see Edmond, Midrigan, and Xu (2015).

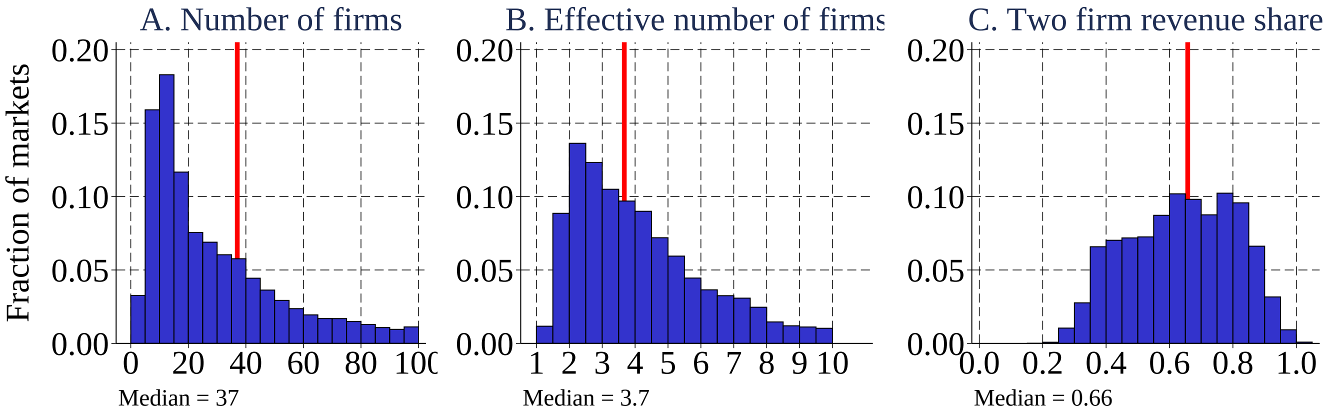

Figure 1: Market concentration in the IRI supermarket data

Notes A market is defined as an IRI product category p within a state s in a quarter t. A firm is defined within market pst by the first 6 digits of a product's barcode. More details on the data can be found in Appendix A. Medians reported in the figure are revenue weighted. Unweighted medians are A. 20, B. 3.7, C. 0.65. **Panel A.** Number of firms is the total number of firms with positive sales in market pst. **Panel B.** Effective number of firms is given by the inverse Herfindahl index h_{pst}^{-1}, where the Herfindahl index is the revenue-share weighted average revenue-share of all firms in the market, $h_{pst} = \sum_{i \in \{pst\}} (rev_{ipst}/rev_{pst})^2$. **Panel C.** Two firm revenue share is the share of total revenue in market pst accruing to the two firms with the highest revenue.

are monopolistically competitive and each sector is populated with a continuum of price-taking firms. Crucially, I calibrate both models to account for the same size and frequency of adjustment found in the IRI good-level data, as well as the same average markup. This is important since prices change frequently and by large amounts on average, and matching these facts strongly curtails the real effects of monetary shocks in a monopolistically competitive model.[3] Since idiosyncratic shocks are large and aggregate shocks are small, this can be thought of as delivering two models that are observationally equivalent in terms of good level price flexibility with respect to good level shocks, then comparing aggregate price flexibility with respect to aggregate shocks.

A number of properties of the oligopoly model emerge, each an important departure from the competitive model. First, the real effects of monetary shocks—measured as the standard deviation of output in an economy with only money shocks—are more than twice as large in the duopoly model. Second, the welfare costs associated with nominal rigidities are five times larger under duopoly. And this difference is not due to price dispersion, which is the focus of policy prescriptions in competitive sticky price models.[4] Third, lower menu costs and sizes of

[3]See papers following Golosov and Lucas (2007), which I discuss in Section 2.

[4]The optimal rule for monetary policy in a standard New-Keynesian model is derived from a second order ap-

idiosyncratic shocks are required to deliver the empirical frequency and size of price change. For reasons that will become clear, this indicates that the model avoids important issues that have arisen in the recent literature that introduces strategic complementarities as a source of amplification into menu cost models. Fourth, that smaller menu costs and shocks are required when comparing models implies that if primitives were in fact the same across different markets then prices would be less flexible in markets characterized by oligopoly. This leads me to examine the empirical relationship between market concentration and price flexibility. Using rich cross-market data and controlling for product-type and region, I find that the conditional correlations I observe in the data support the predictions of the model.[5]

Each of these results is due to the interaction of three key features of the model. First, when firms are imperfectly competitive and households have a low ability to substitute across different sectors, there naturally arise strategic complementarities in price setting. If a competitor's price is high, a firm's static best response is also a high price, understanding that increasing the sector's price index leads to little substitution away from the sector. In the absence of nominal rigidities, however, the frictionless Bertrand Nash equilibrium is obtained and money is neutral. Firms cannot credibly follow a strategy in which they do not under-cut their competitor. Menu costs, the second feature, reduce the value of under-cutting a competitor's price. A dynamic model, the third feature, implies that firms can post high prices understanding their competitor can and will follow them in future periods, with the cost of adjustment lending credibility to this strategy. This links the prices of the two firms. As firms' idiosyncratic productivities diverge and nominal prices remain fixed due to menu costs, the value and size of their optimal price adjustment depends on the price of their competitor. As studied first by Maskin and Tirole (1988b) in the context of alternating pricing, and Jun and Vives (2004) in the context of convex adjustment costs, this leads to *dynamic strategic complementarities* in pricing. How do these dynamic strategic complementarities lead to the main results in the paper?[6]

proximation of the household's utility function around a flexible price zero-inflation steady-state. It depends only on inflation in so far as inflation causes sub-optimally large (small) amounts of labor to be used in the production of goods that have sub-optimally low (high) prices. That is, there is a *second order* welfare cost of inflation that emerges entirely due to price dispersion.

[5] Due to the endogeneity of market structure, pushing these conditional correlations towards causal statements is beyond the scope of this paper.

[6] Neither of these papers consider idiosyncratic shocks at the firm level and provide qualitative results.

1. Real effects of monetary shocks The key contribution of the paper is to aggregate an economy of oligopolistic sectors into an equilibrium macroeconomic model and understand how this dynamic strategic complementarity can be important for macroeconomic dynamics. Following an increase in the money supply, equilibrium aggregate nominal costs increase. In the monopolistically competitive model this leads more firms with already low prices to increase their price: an extensive margin effect that leads to a quick response in the aggregate price level. These firms also increase their prices by more to make up for increased nominal costs: an intensive margin effect. As shown in Golosov and Lucas (2007), when the average size of price changes is large—as it is in the data—this leads to a swift response in the aggregate price.

Dynamic strategic complementarities dampen these effects at firms with low prices. In my model, these marginal firms face a head-to-head inframarginal competitor in their sector. If this competitor's initial price is high, then the equilibrium increase in nominal cost is welcomed by their competitor, reducing their probability and size of adjustment. This affects the behavior of the marginal firm. With its competitor's nominal price becoming more rigid, and the aggregate price level increasing, its competitor's relative price falls. In a nominal economy, the dynamic strategic complementarity is in these relative prices. The marginal firm's increase in the size and value of a price due to higher aggregate marginal costs is tempered by the falling relative price at its competitor.[7] The price response of firms that most undo the real effects of monetary shocks is dampened in the duopoly model.

To account for these results I decompose the response of the aggregate price level, an exercise in the spirit of Caballero and Engel (2007).[8] When aggregated over all sectors, the decomposition shows that the extensive and intensive margins of adjustment are dampened equally. However between sectors, these vary substantially. In sectors where firms initially both have low prices—relative to the distribution of prices in the economy—the duopoly model leads to larger price responses. In equilibrium one firm increasing its price incentivizes its competitor to do so. Some low priced firms drag other low priced firms into adjusting their price following

[7]An additional effect is as follows, worth mentioning here. In the sectoral equilibrium, firms with low prices increase them both due to idiosyncratic productivity shocks and to reduce the incentive of high priced firms to undercut them. This behavior trades off short-run market share for long-run higher prices in the sector. With its competitor moving towards its optimal relative price, this incentive is weaker, also dampening the incentive of a price increase. I am currently working towards separating out these two, linked, forces.

[8]This decomposition has provided an accounting tool for this class of models and has been used by Midrigan (2011), Alvarez and Lippi (2014) and others.

the shock, increasing the extensive margin response. Conditional on both adjusting their price, the size of adjustment is also larger, increasing the intensive margin response. These types of sectors contribute substantially towards smaller output responses in the duopoly model. Quantitatively, however, they are offset by sectors of the type previously described, in which one firm's price is low, and the other's high. This exercise makes clear the value of an equilibrium exercise in which all sectors of the economy are aggregated. To focus on a particular sector one might bias either upwards or downwards the forecast response of prices and output to a shock to aggregate marginal cost.

2. Welfare losses of nominal rigidity The dynamic strategic complementarity that arise in the equilibrium of the oligopoly model features large first order welfare losses relative to an economy with no nominal rigidity. In the presence of nominal rigidity, firms attain higher markups than the frictionless equlilibrium. The cost of changing prices wipes out the benefits of deviating in the direction of the firm's best response: which is to undercut its competitor. Markups are the relevant measure of 'real prices' in the economy. Quantitatively, these are 10ppt higher than in the economy with menu costs set to zero.[9] And output is therefore about 10ppt lower. This implies that model has rich implications not only for the dynamics of aggregate output, but also its level. And—although not a subject studied here—invites thinking about how policies may affect both. As an example, very high trend inflation, would weaken the dynamic strategic complementarity.[10] On the one hand this would reduce the real effects of a monetary expansion. On the other hand, it would restore these first order welfare losses.[11]

An extension of this result is that—within a certain range—firms may prefer to face larger nominal rigidities. As described above, if menu costs were zero then firms would repeat the

[9] To put this 10ppt in some context within the model: in a frictionless equilibrium under cooperative strategies (collusion), markups would be 200ppt higher than the frictionless equilibrium under non-cooperative strategies. The *presence* of menu costs allow non-cooperative firms to attain higher markups but this is limited by the *size* of the menu costs, which in turn is limited by the data on price adjustment frequency.

[10] If trend inflation were high enough, then all firms in the economy would change their price every period. If all firms are changing their price every period, then the only equilibrium is the frictionless Nash-Bertrand equilibrium and there is no wedge between the frictionless and average markup.

[11] In both the monopolistically competitive and oligopoly models there are also output losses which come from price dispersion. These are equal in both models because, roughly speaking, both have the same average size of price change. In both models this leads to output being 2ppt lower than in the absence of nominal rigidity. The output losses due to the dynamic strategic complementarity are ten times larger than those coming from price dispersion.

static Nash equilibrium of the Bertrand game. As menu costs increase, firms can commit to higher prices: average markups increase as does the value of the firm. As menu costs increase further, the inability to respond to idiosyncratic and aggregate shocks offsets the role of the menu cost in commitment and the value of the firm falls. Here I can quantify these forces in a realistic model of firm price dynamics. I find that in the empirically relevant range of menu costs the commitment effect dominates and the value of the firm is increasing in menu costs. In this sense the model provides a novel rationale for investment in advertising and other such activities that increase the cost of adjustment.

3. Strategic complementarities and menu cost models It has long been understood that some source of 'real rigidity' is needed to generate substantial real effects of monetary shocks (Ball and Romer, 1990; Woodford, 2003). Quantitatively, since the frequency of price change is large, then some other force must stagger the adjustment in prices. Recently a number of papers have tested old ideas for generating strategic complementarity within the Golosov and Lucas (2007) framework, again constraining the models quantitatively by the large size and frequency of price change in good-level data. Klenow and Willis (2016) study a non-CES demand aggregator which gives rise to variable markups through demand.[12] Burstein and Hellwig (2007) study the case of decreasing-returns to scale in production which gives rise to variable markups through costs. Their findings—summarized by Nakamura and Steinsson (2010)—are that strategic complementarities can not be a source of propagation due to the requirement of unreasonably large sizes of firm level shocks in order to match the good-level data on price adjustment. One result of this paper is to describe a situation where this is not the case: firm level shocks and menu costs are *smaller* in the duopoly model, yet amplification is still achieved through strategic complementarities. As I explain later, this is due to the strategic complementarities existing between two firms' prices, rather than a firm's price and the aggregate price. When this is the case, these well understood problems slacken.

[12] A literature in international economics has employed the same Kimball (1995) demand specification to study pass-through of exchange rate, or foreign, shocks to domestic prices. See: Gopinath and Itskhoki (2011), Berger and Vavra (2013). At the end of this paper I note how my model may be simply extended to study this question.

4. Empirical relationship As noted above, lower menu costs are required to generate the same level of observed price rigidity in the duopoly model. Firms with low prices are reluctant to increase their price due to short-run market share incentives. Firms with high prices are reluctant to decrease their prices as to do so would reduce the incentive of its competitor to choose a high price on adjustment, reducing average prices. This has some empirical content. The model predicts that when comparing markets with the same menu cost, strategic behavior leads to less flexible prices. This study considers only the cases of one, two and infinitely many firms, where in the limiting cases firms are non-strategic and strategic in between. This predicts a U-shape relationship between market concentration and the frequency of price adjustment.

It is beyond the scope of this paper to try to document a *causal* relationship between market concentration and price flexibility. Market structure is itself endogenous and I do not aim to address this here. However I do document that, within markets that may plausibly have the same primitives (menu costs, shocks, etc), there is a strong correlation between concentration and flexibility in the data . In particular, I consider within product-group variation across regional markets, and as an alternative, within region variation across product-groups. Moreover I consider observations from the same stores, controlling for store effects by construction. The structure of this correlation is consistent with the causal implications of the model: there is U-shape relationship between market concentration and frequency of price adjustment.[13]

Structure The remainder of the paper is organized as follows. Section 2 reviews the relevant literature. Section 3 presents the model. Section 4 develops intuition for the main results of the paper by studying a simplified version of the model. Section 5 describes the calibration strategy followed in order to compare the two models. Section 6 describes the main result, how this is robust to different assumptions and calibrations, and how the amplification of monetary shocks in the duopoly model differs to existing mechanisms that get larger real effects from a menu cost model. Section 7 describes the two additional results regarding welfare costs of nominal rigidity and endogenous price stickiness. Section 8 tests the model's predictions for the cross-sectional empirical relationship between market concentration and price flexibility. Section 9 shows how the model may be extended to answer whether endogenous entry leads

[13]Similarly I document a hump-shaped relationship between concentration and size of adjustment. Consistent with the menu cost model: size and frequency of price adjustment are negatively correlated in the data.

to larger or smaller aggregate price stickiness.[14] Section 10 concludes.

2 Literature

This paper is situated in two distinct literatures: (i) the strand of monetary economics following Golosov and Lucas (2007) that has studied the ability of menu cost models of price adjustment to explain monetary non-neutrality, (ii) a literature on dynamic games of price setting. Additionally the paper contributes new empirical facts to a recent literature that studies heterogeneity in price flexibility.

Equilibrium models of monopolistic competition and menu costs of price adjustment

Golosov and Lucas (2007) show that in an equilibrium menu cost model of price adjustment that matches the large size and frequency of price change in good-level data, shocks to nominal demand lead to small output effects. A number of papers show that extensions of the Golosov and Lucas (2007) model can generate larger real effects while matching the same price data. Midrigan (2011) and Alvarez and Lippi (2014) show that once the model accounts for small price changes it can generate output responses similar to a Calvo model of price adjustment calibrated to the same moments.[15] Nakamura and Steinsson (2010) show that in the Golosov and Lucas (2007) model, the degree of monetary non-neutrality is convex in the degree of price flexibility. Noting that different sectors have different degrees of price flexibility they calibrate a multi-sector model and through this Jensen's inequality effect generate large real effects of monetary shocks. Furthermore, like Klenow and Willis (2016) and Burstein and Hellwig (2007) the authors conclude that *macro* strategic complementarities that come through slow responses of input prices are the most likely candidate for monetary non-neutrality relative to other sources of real rigidities.[16] The source of strategic complementarity I study in this paper is different and uniquely derives from the interaction of (i) non-atomistic market structure, (ii)

[14] Results from this extensions will be included in updated versions of this paper.

[15] Both Midrigan (2011) and Alvarez and Lippi (2014) achieve this through multi-product firms with economies of scope in price change. Midrigan (2011) shows that the precise way that one accounts for small price changes is inconsequential. He shows that a single-product firm facing random menu costs can match the distribution of price changes and also delivers large output responses.

[16] Nakamura and Steinsson (2010) follow the formulation of the *round-a-bout production structure* of Basu (1995).

menu costs. I return to a more precise comparison with these papers following my results in Section 6.

Partial equilibrium dynamic models of oligopoly with nominal rigidities

The industrial organization literature has understood that nominal rigidities in price setting induce an intertemporal complementarity in price setting when markets are oligopolistic. Maskin and Tirole (1988b) first make this point. In a highly stylized price setting environment where firms have an exogenous short-run commitment to prices, Markov Perfect equilibrium policies of firms may accommodate higher prices than in the frictionless static Nash equilibrium. Jun and Vives (2004) confirm this result in a differential game with convex costs of price adjustment: prices are strategic complements and adjustment costs allow firms to commit to high price strategies should their competitor follow them, which they do in equilibrium. In an empirical partial equilibrium setting Kano (2013) makes a similar point in an environment where firms face fixed costs of adjustment. However the fact that dynamic oligopoly generates additional nominal rigidity is insufficient for this paper, in which I aim to compare duopoly and monopolistically competitive market structures. An accurate comparison demands that they account for the same observed level of nominal rigidity in prices.

Nakamura and Zerom (2010) and Neiman (2011) study partial equilibrium models of oligopolistic market structures at the sectoral level in which firms face menu costs of price adjustment. Nakamura and Zerom (2010) study the behavior of three firms subject to only sectoral shocks to the costs of inputs. To align with the monetary economics literature I assume that firms face shocks to both idiosyncratic and aggregate demand and consider the model in general equilibrium. Neiman (2011) considers a model of duopoly with only idiosyncratic shocks, but does not bring the model to data on size and frequency of price adjustment and does not compare the implications of the model against a monopolistically competitive benchmark. Moreover, neither paper focuses on the inter-temporal strategic complementarities and their effects on average markups.

Cross-sectional facts regarding price stickiness

A recent literature has documented cross-sectional heterogeneity in price flexibility. I contribute to this literature in two ways. First I show that even within a sector—in my case grocery items—price flexibility varies substantially (i) across product categories within regions, (ii) across regions within product categories. Second I show that this variation is systematic. Price flexibility is related to market concentration in a U-shaped way. Markets with very few or very many firms have high price flexibility, and those with a small number of firms have lower price flexibility. I show that my model is consistent with this new correlation, predicting higher (lower) price flexibility when firms are atomistic (large).

Existing models that incorporate cross-sectional heterogeneity in price flexibility assume this heterogeneity comes through differences in the magnitude of the nominal rigidity. In their multi-sector menu cost model, Nakamura and Steinsson (2010) account for the unconditional dispersion in price flexibility with differences in menu costs. Studying New-Keynesian models Weber (2016) and Gorodnichenko and Weber (2016) follow a similar approach, allowing the exogenous probability of price adjustment to vary across sectors. In an international menu cost model Berger and Vavra (2013) show that heterogeneity in the curvature of demand rather than menu costs can jointly explain the positive cross-sectional relationship between price flexibility and pass-through. For the same levels of menu cost I find that a menu cost model generates endogenously less flexible prices under duopoly.

3 Model

The baseline model studied in this paper can be framed in three ways. As a menu cost model of price adjustment following Golosov and Lucas (2007), extended to allow for oligopoly at the sectoral level. As a model of oligopolistic competition under an Atkeson and Burstein (2008) market structure, extended to include nominal rigidity in the form of a menu cost of changing prices. Or as a model of dynamic oligopoly with nominal rigidity as in Nakamura and Zerom (2010), with persistent idiosyncratic firm level shocks and situated in an equilibrium monetary business cycle model.

3.1 Environment and timing

Time is discrete. The economy is populated with two types of agents: households and firms. Households are identical, consume goods, supply labor, and hold shares in a portfolio of all firms in the economy. Firms are organized in a continuum of sectors which produce differentiated goods and are indexed $j \in [0,1]$. Within each sector two firms indexed $i \in \{1,2\}$ compete in a dynamic oligopoly and produce differentiated goods. Households have nested CES preferences for goods: across- and then within-sectors. Production is via a constant returns production function in labor. Each period each firm draws a menu cost $\xi_{ijt} \sim H(\xi)$ which is the private information of firm i, and may change their price p_{ijt} conditional on paying ξ_{ijt}. Uncertainty comes in the form of shocks to the money supply M_t, and a shock to preferences for each good z_{ijt}. Both follow first order stochastic processes.

Regarding notation, throughout I write agents' problems recursively, dropping the subscript t. The aggregate state is denoted $\mathbf{S} \in \mathcal{S}$ and the vector of sectoral state variables $s \in S$. The distribution of firms over sectoral states is given by the measure $\lambda(s)$. I write all integrals over the continuum of sectors as integrating s over $\lambda(s)$ rather than integrating j over a uniform density on $[0,1]$.

3.2 Household

Problem Given prices for all goods in all sectors $\{p_i(s,\mathbf{S})\}_{i\in\{1,2\}}$, wage $W(\mathbf{S})$, the price of shares in the stock-market $\Omega(\mathbf{S})$, aggregate dividends $\Pi(\mathbf{S})$, and a law of motion for the aggregate state $\mathbf{S}' \sim \Gamma(\mathbf{S}'|\mathbf{S})$, households choose consumption of both goods in each sector $\{c_i(s)\}_{i\in\{1,2\},s\in S}$, labor supply N and shares X to solve the following recursive problem:

$$\mathbf{W}(\mathbf{S},X) = \max_{c_i(s),N,X'} \log C - N + \beta\mathbb{E}\Big[\mathbf{W}\left(\mathbf{S}',X'\right)\Big]$$

$$\text{where} \qquad C = \left[\int \mathbf{c}(s)^{\frac{\theta-1}{\theta}} d\lambda(s)\right]^{\frac{\theta}{\theta-1}}$$

$$\mathbf{c}(s) = \left[\Big(z_1(s)c_1(s)\Big)^{\frac{\eta-1}{\eta}} + \Big(z_2(s)c_2(s)\Big)^{\frac{\eta-1}{\eta}}\right]^{\frac{\eta}{\eta-1}}$$

subject to the nominal resource constraint

$$\int_0^1 \Big[p_1(s,\mathbf{S})c_1(s) + p_2(s,\mathbf{S})c_2(s)\Big]\, d\lambda(s) + \Omega(\mathbf{S})X' \;\; \leq \;\; W(\mathbf{S})N + \Big(\Omega(\mathbf{S}) + \Pi(\mathbf{S})\Big)X.$$

Households discount the future at rate β, have time separable utility and derive period utility from consumption adjusted for the disutility of work, which is linear in labor.[17] Utility from consumption is logarithmic in a CES aggregator of consumption utility from the continuum of sectors. The cross-sector elasticity of demand is denoted $\theta > 1$. Utility from sector j goods is given by a CES utility function over the two firms' goods with within-sector elasticity of demand $\eta > 1$. These elasticities are ranked $\eta > \theta$ indicating that the household can more freely substitute between goods within a sector (Pepsi vs. Coke) than across sectors (Soda vs. Laundry detergent). Finally, household preferences for goods are subject to a taste shifter $z_i(s)$ which evolve according to a random-walk

$$\log z_i'(s) = \log z_i(s) + \sigma_z \varepsilon_i', \quad \varepsilon_i \sim \mathcal{N}(0,1), \tag{1}$$

where innovations ε_i are independent over firms, sectors, and time.[18]

Solution The solution to the household problem consists of demand functions for each firm's output $d_i(s,\mathbf{S})$, a labor supply condition $N(S)$, and an equilibrium share price $\Omega(S)$ which will be used to price firm payoffs. Demand functions are given by

$$\begin{aligned} d_i(s,\mathbf{S}) &= z_i(s)^{\eta-1}\left(\frac{p_i(s,\mathbf{S})}{\mathbf{p}(s,\mathbf{S})}\right)^{-\eta}\left(\frac{\mathbf{p}(s,\mathbf{S})}{P(\mathbf{S})}\right)^{-\theta} C(\mathbf{S}), \qquad (2)\\ \text{where} \quad P(\mathbf{S}) &= \left[\int \mathbf{p}(s,\mathbf{S})^{1-\theta} d\lambda(s)\right]^{\frac{1}{1-\theta}}, \\ \mathbf{p}(s,\mathbf{S}) &= \left[\left(\frac{p_1(s,\mathbf{S})}{z_1(s)}\right)^{1-\eta} + \left(\frac{p_2(s,\mathbf{S})}{z_2(s)}\right)^{1-\eta}\right]^{\frac{1}{1-\eta}}. \end{aligned}$$

Aggregate real consumption is $C(\mathbf{S})$. The allocation of $C(\mathbf{S})$ to sector s depends on the level of the sector s price index $\mathbf{p}(s,\mathbf{S})$ relative to the aggregate price index $P(\mathbf{S})$. The allocation of

[17] Note that I do not include a parameter controlling the utility cost of labor (i.e. $U(C,N) = \log C - \psi N$). In this environment ψ can be normalized to one.

[18] The random walk assumption on these shocks is convenient but also realistic given that I will be solving the model at a monthly frequency.

expenditure to firm i is then determined by $z_i(s)$, and the level of firm i's price relative to the sectoral price $\mathbf{p}(s,\mathbf{S})$.

The aggregate price index satisfies $P(\mathbf{S})C(\mathbf{S}) = \int \left[p_1(s,\mathbf{S})c_1(s,\mathbf{S}) + p_2(s,\mathbf{S})c_2(s,\mathbf{S})\right] d\lambda(s)$, such that $P(\mathbf{S})C(\mathbf{S})$ is equal to aggregate nominal consumption. I assume that nominal consumption must be paid using money M such that $M(\mathbf{S}) = P(\mathbf{S})C(\mathbf{S})$.[19] The supply of money is exogenous and evolves according to a growth rate $g' = M'/M$ which follows a first order autoregressive process in logs

$$\log g' = (1-\rho_g)\log \bar{g} + \rho_g \log g + \sigma_g \varepsilon', \quad \varepsilon' \sim \mathcal{N}(0,1). \tag{3}$$

The nominal economy will be trend stationary around the steady-state level of money growth $\bar{g} > 0$. An intratemporal condition determines labor supply and intertemporal Euler equation prices shares

$$W(\mathbf{S}) = \frac{P(\mathbf{S})}{u'(C(\mathbf{S}))} = P(\mathbf{S})C(\mathbf{S}), \tag{4}$$

$$\Omega(\mathbf{S}) = \beta\mathbb{E}\left[\frac{u'(C(\mathbf{S}'))/P(\mathbf{S}')}{u'(C(\mathbf{S}))/P(\mathbf{S})}\left(\Omega(\mathbf{S}') + \Pi(\mathbf{S}')\right)\Big|\mathbf{S}\right]. \tag{5}$$

Jointly these imply that the discount factor applied to firm payoffs $Q(\mathbf{S},\mathbf{S}')$ can be written $Q(\mathbf{S},\mathbf{S}') = \beta\frac{W(\mathbf{S})}{W(\mathbf{S}')}$. The household discounts states where wage growth is high, since consumption is relatively high in these states.

3.3 Firms

State variables The period begins with the realization of the sectoral state vector s which contains both firms' (i) previous prices p_i, p_{-i} (iii) and current preference shocks z_i, z_{-i}.

Timing Consider the problem for firm i with direct competitor denoted $-i$. Firm i draws a menu cost $\xi_i \sim H(\xi)$ which is private information. Then, at the same time as its competitor, chooses whether to adjust its price and conditional on adjustment the new price level p_i'. Prices

[19]An alternative approach would be to assume that money holdings enter the utility function as in Golosov and Lucas (2007). As noted in that paper, as long as utility is separable, the disutility of labor is linear and the utility of money is logarithmic one obtains the same equilibrium conditions regarding the wage, nominal consumption and money supply as studied here.

then become public and each firm produces and sells the quantity demanded by the household. At the end of the period, preference shocks evolve stochastically to z_i' and z_{-i}' according to (1). The new sectoral state is $s' = \left(p_i', p_{-i}', z_i', z_{-i}'\right)$.

In making these decisions firm i understands the equilibrium policies of its direct competitor. These are given by an indicator for price adjustment $\phi_{-i}(s, \mathbf{S}, \xi_{-i}) \in \{0,1\}$ and price conditional on adjustment $p_{-i}'(s, \mathbf{S})$ (since the menu cost is sunk, the price conditional on adjustment is independent of the menu cost). This description of the environment explicitly restricts firm policies to depend only on only pay-off relevant information $(s, \mathbf{S})$, that is they are *Markov strategies*.[20] A richer dependency of policies on the history of firm behavior is beyond the scope of this paper.

Problem Let $V_i(s, \mathbf{S}, \xi)$ denote the present discounted expected value of nominal profits of firm i after the realization of the sectoral and aggregate states $(s, \mathbf{S})$ and its menu cost ξ. Then $V_i(s, \mathbf{S}, \xi)$ satisfies the following recursion

$$\begin{aligned} V_i\left(s, \mathbf{S}, \xi\right) &= \max \left\{ V_i^{adj}\left(s, \mathbf{S}\right) - W(\mathbf{S})\xi,\ V_i^{stay}\left(s, \mathbf{S}\right) \right\}, \qquad (6) \\ V_i^{adj}\left(s, \mathbf{S}\right) &= \max_{p_i'} \int \Bigg[\phi_{-i}(s, \mathbf{S}, \xi_{-i}) \left\{ \pi_i\left(p_i', p_{-i}'(s, \mathbf{S}), s, \mathbf{S}\right) + \mathbb{E}\left[Q(\mathbf{S}, \mathbf{S}') V_i\left(s', \mathbf{S}', \xi'\right) \right] \right\} \\ &\quad + \left(1 - \phi_{-i}(s, \mathbf{S}, \xi_{-i})\right) \left\{ \pi_i\left(p_i', p_{-i}, s, \mathbf{S}\right) + \mathbb{E}\left[Q(\mathbf{S}, \mathbf{S}') V_i\left(s', \mathbf{S}', \xi'\right) \right] \right\} \Bigg] dH(\xi_{-i}), \\ \pi_i\left(p_i, p_{-i}, s, S\right) &= d_i\left(p_i', p_{-i}, s, \mathbf{S}\right)\left(p_i - z_i(s) W(\mathbf{S})\right), \\ S' &\sim \Gamma\left(\mathbf{S}' | \mathbf{S}\right). \end{aligned}$$

The first line states the extensive margin problem, where adjustment requires a payment of menu cost ξ in units of labor. The value of adjustment is independent of the menu cost and requires choosing the new price p_i'. When making these decisions the firm must integrate out the unobserved states of its competitor—the menu cost ξ_{-i}—and take account of how its competitor's pricing decision effects current payoffs and the evolution of s'. The term in braces on the second (third) line gives the flow nominal profits plus continuation value of the firm if its

[20] In the words off Maskin and Tirole (1988a), "Markov strategies...depend on as little as possible, while still being consistent with rationality".

competitor does (does not) adjust its price p_{-i}. The value of non-adjustment V_i^{stay} is identical to adjustment with the restriction $p_i' = p_i$.

The flow payoff introduces a role for $z_i(s)$ in costs. As in Midrigan (2011) I assume that $z_i(s)$— which increases demand for the good with an elasticity of $(\eta - 1)$ — also increases total costs with a unit elasticity. This technical assumption will allow me to reduce the state-space of the firm's problem while still ensuring that the primary structural interpretation of the shock is as a demand shock.

The firm discounts future dividends by the household's nominal discount factor $Q(\mathbf{S}, \mathbf{S}')$, and expectations are taken with respect to the equilibrium transition density $\Gamma(\mathbf{S}'|\mathbf{S})$. Nominal profit π_i depends on aggregate consumption $C(\mathbf{S})$ and aggregate price-index $P(\mathbf{S})$ which the firm understands as functions of aggregate state variables.

Before proceeding, note that the fact that the intensive margin pricing decision p'_{-i} will also be independent of the menu cost means that we can integrate out ξ_{-i} when computing firm i's payoff. This means that we can replace ϕ_{-i} with the probability that firm $-i$ changes its price, $\gamma_{-i}(s, \mathbf{S}) = \int \phi_{-i}(s, \mathbf{S}, \xi_{-i}) dH(\xi_{-i})$. Since ξ_i is *iid* we can also integrate it out of firm i's Bellman equation:

$$
\begin{aligned}
V_i(s, \mathbf{S}) &= \int \max \left\{ V_i^{adj}(s, \mathbf{S}) - W(\mathbf{S})\xi,\ V_i^{stay}(s, \mathbf{S}) \right\} dH(\xi), \\
V_i^{adj}(s, \mathbf{S}) &= \max_{p_i'} \ \gamma_{-i}(s, \mathbf{S}) \left\{ \pi_i\left(p_i', p'_{-i}(s, \mathbf{S}), s, \mathbf{S}\right) + \mathbb{E}\left[Q(\mathbf{S}, \mathbf{S}') V_i(s', \mathbf{S}') \right] \right\} \\
&\quad + \left(1 - \gamma_{-i}(s, \mathbf{S})\right) \left\{ \pi_i\left(p_i', p_{-i}, s, \mathbf{S}\right) + \mathbb{E}\left[Q(\mathbf{S}, \mathbf{S}') V_i(s', \mathbf{S}') \right] \right\}.
\end{aligned}
\tag{7}
$$

The solution to this problem is firm i's price conditional on adjustment $p_i'(s, S)$ and probability of price adjustment $\gamma_i(s, \mathbf{S})$ which is given by

$$
\gamma_i(s, \mathbf{S}) = \mathbb{P}\left[\xi_i W(\mathbf{S}) \leq V^i_{adj}(s, \mathbf{S}) - V^i_{stay}(s, \mathbf{S}) \right] = H\left(\frac{1}{W(\mathbf{S})} \left[V^i_{adj}(s, \mathbf{S}) - V^i_{stay}(s, \mathbf{S}) \right] \right). \tag{8}
$$

3.4 Equilibrium

Given the above, the aggregate state vector $\mathbf{S}$ must contain the level of nominal demand M, its growth rate g, and the distribution of sectors over sectoral state variables λ. A *recursive equilibrium* consists of

(i) Household demand functions $d^i(s, \mathbf{S})$

(ii) Firm value functions $V_i(s, \mathbf{S})$ and policies $p'_i(s, \mathbf{S})$, $\gamma_i(s, \mathbf{S})$

(iii) Wage, labor supply, price index, consumption and discount factor functions

$$W(\mathbf{S}),\ N(\mathbf{S}),\ P(\mathbf{S}),\ C(\mathbf{S}),\ Q(\mathbf{S}, \mathbf{S}')$$

(iv) Law of motion $\Gamma(\mathbf{S}, \mathbf{S}')$ for the aggregate state $\mathbf{S} = (z, g, M, \lambda)$

such that

(a) Household demand functions are consistent with household optimization condition (2)

(b) The functions in (iii) are consistent with household optimality conditions (4)

(c) Given household demand functions, competitor policies, wage, price, consumption, discount factor functions, and Γ: p'_i, γ_i are consistent with firm i optimization and value function V_i (7)

(d) The price function is equal to the household price index under firm policies

$$\begin{aligned} P(\mathbf{S}) &= \left[\int \mathbb{E}_{\gamma_1(s,\mathbf{S}),\gamma_2(s,\mathbf{S})}\left[\mathbf{p}\,(s, \mathbf{S})^{1-\theta}\right] d\lambda\,(s)\right]^{\frac{1}{1-\theta}} \\ \mathbf{p}(s, \mathbf{S}) &= \left[\left(\frac{p'_1(s, \mathbf{S})}{z_1(s)}\right)^{1-\eta} + \left(\frac{p'_2(s, \mathbf{S})}{z_2(s)}\right)^{1-\eta}\right]^{\frac{1}{1-\eta}} \end{aligned}$$

(e) The household holds all shares $X(\mathbf{S}) = 1$ and the price of shares is consistent with (4)

(e) The stochastic law of motion for g and path for M are determined by (3), and nominal demand satisfies $P(\mathbf{S})C(\mathbf{S}) = M(\mathbf{S})$

(f) The law of motion for λ is consistent with firm policies. Let $X = P_1 \times P_2 \times Z \times Z \in \mathbb{R}^4_+$, and the corresponding set of Borel sigma algebras on X be given by $\mathcal{X} = \mathcal{P}_1 \times \mathcal{P}_2 \times \mathcal{Z}_1 \times \mathcal{Z}_2$. Then $\lambda : \mathcal{X} \to [0, 1]$ and obeys the following law of motion for all subsets of $\mathcal{X}$[21]

$$\lambda'(\mathcal{X}) = \int_X \mathbb{E}_{\gamma_1(s,\mathbf{S}),\gamma_2(s,\mathbf{S})}\left[\mathbf{1}_{[p_1(s,\mathbf{S})\in\mathcal{P}_1,\, p_2(s,\mathbf{S})\in\mathcal{P}_2]}\right] G(z_1, \mathcal{Z}_1)G(z_2, \mathcal{Z}_2)d\lambda(s)$$

[21] In this definition $\mathbb{E}_{\gamma_1(s,\mathbf{S}),\gamma_2(s,\mathbf{S})}\left[f(s, \mathbf{S})\right]$ is the expectation of f under the sector s probabilities of price adjustment.

This definition of equilibrium is an extension of the standard definition of a recursive competitive equilibrium found in Ljungqvist and Sargent (2012). Firms are atomistic and behave *competitively* with respect to firms in other sectors of the economy. However with respect to its competitor in sector j, firm i understands the affect of firm j's actions on current period payoffs and the evolution of the sectoral state s. Condition (c) requires that the policies of firms within each sector are Markov Perfect. The relevant measure in the economy is then the measure over *sectoral* state variables which include both firm prices and sectoral demand.

3.5 Monopolistically competitive model

The monopolistically competitive model is the same as above except with infinitely many firms in each sector. In this model firm i in sector j belongs to a continuum of firms $i \in [0,1]$. These firms behave atomistically with respect to their sector and so the relevant state variables for the firm is limited to its own level of demand z_i and past price p_i. The demand system from the household's problem is then

$$
\begin{aligned}
d(s,\mathbf{S}) &= z(s)^{\eta-1}\left(\frac{p(s,\mathbf{S})}{\mathbf{p}_j(\mathbf{S})}\right)^{-\eta}\left(\frac{\mathbf{p}_j(\mathbf{S})}{P(\mathbf{S})}\right)^{-\theta} C(\mathbf{S}) \qquad (9)\\
\text{where} \quad P(\mathbf{S}) &= \left[\int_0^1 \mathbf{p}_j(\mathbf{S})^{1-\theta} dj\right]^{\frac{1}{1-\theta}}\\
\mathbf{p}_j(\mathbf{S}) &= \left[\int \left(\frac{p(s,\mathbf{S})}{z(s)}\right)^{1-\eta} d\lambda_j(s)\right]^{\frac{1}{1-\eta}}.
\end{aligned}
$$

In the monopolistically competitive model changes in the firm's price are correctly perceived to not affect the sectoral price $\mathbf{p}_j$. Moreover, since the parameters of the firm environment are the same in all sectors and idiosyncratic shocks wash out at the sectoral level, the distribution of firms λ_j is the same in all sectors. This implies that the aggregate price $P(\mathbf{S}) = \mathbf{p}_j(\mathbf{S})$ and the cross-sector elasticity of demand θ appears nowhere in the firm problem or equilibrium conditions.

Note the connection between monopolistic competition and another market structure: sectoral monopoly. With one firm in each market the sectoral price index is simply the monopolist's price and the within-sector elasticity of demand η is redundant. A monopolistically competitive model under $\eta = \eta_{MC}$ will therefore be identical in firm level and aggregate dynamics to a model of sectoral monopoly with $\theta = \eta_{MC}$. I return to this point when discussing the model's implications for the empirical relationship between market concentration and price flexibility in Section 8.

3.6 From nominal prices p to real prices μ

In Appendix B I show that the firm's problem can be stated as one in which the sectoral state vector is reduced to the two firms' real prices. Since households are paid in terms of nominal wages and nominal profits it makes sense that the equilibrium can also be restated only in terms of real prices and quantities.

A firm's real price is the ratio of its nominal price to nominal cost, or its markup $\mu_{ij} = p_{ij}/(z_{ij}W)$. The sectoral markup $\mu_j = \mathbf{p}_j/W$ can then be written $\mu_j = \left[\mu_{1j}^{1-\eta} + \mu_{2j}^{1-\eta}\right]^{\frac{1}{1-\eta}}$, while the aggregate markup $\mu = P/W$ can be expressed as a CES aggregator over sectoral markups $\mu = \left[\int_0^1 \mu_j^{1-\theta} dj\right]^{\frac{1}{1-\theta}}$. This implies that all equilibrium conditions can also be stated in markups rather than prices. Note that the equilibrium conditions $W = PC = M$ imply that $\mu = 1/C$: an increase in money which causes the aggregate markup to fall, causes real output to increase.

Using these, the profit function of the firm can be normalized by the wage and written

$$\frac{\pi\Big(\mu_i, \mu_{-i}, \mathbf{S}\Big)}{W(\mathbf{S})} = \left(\frac{\mu_i}{\mu_j(\mu_i, \mu_{-i})}\right)^{-\eta} \left(\frac{\mu_j(\mu_i, \mu_{-i})}{\mu(\mathbf{S})}\right)^{-\theta} \Big(\mu_i - 1\Big)\frac{1}{\mu(\mathbf{S})} = \tilde{\pi}\Big(\mu_i, \mu_{-i}\Big)\mu(\mathbf{S})^{\theta-1}.$$

The discount factor is $Q(\mathbf{S}, \mathbf{S}) = \beta W(\mathbf{S})/W(\mathbf{S}')$, making it straight forward to similarly normalize value functions by the wage $v(s, \mathbf{S}) = V(s, \mathbf{S})/W(\mathbf{S})$. This renders the firm problem stationary and leads to the following expression for the value of the adjusting firm

$$v_i^{adj}\Big(\mu_i, \mu_{-i}, \mathbf{S}\Big) = \max_{\mu_i'} \mathbb{E}_{\mu_{-i}', \mathbf{S}'}\left[\tilde{\pi}\Big(\mu_i', \mu_{-i}'\Big)\mu(\mathbf{S})^{\theta-1} + \beta v_i\left(\frac{\mu_i'}{g'e^{\varepsilon_i'}} \frac{\mu_{-i}'}{g'e^{\varepsilon_{-i}'}}, \mathbf{S}'\right)\right]. \tag{10}$$

This formulation of the problem gives a clear interpretation of the two shocks hitting the firm. First, a random-walk shock to z_i shows up as a permanent *iid* shock to the markup of firm i should the firm not adjust its price. As most firms will not adjust prices each period, this leads to a distribution of real prices. Second, a single positive innovation to money growth causes g to increase then return to steady-state $\bar{g}$ at rate ρ_g. Absent adjustment both firms' markups would decline on impact and then continue to decline at a decreasing rate until they reach some permanently lower level. Firms pay a real cost ξ to adjust their markup.

The solution to this problem requires a pricing function for the aggregate markup $\mu(\mathbf{S})$, implying that the infinite dimensional distribution of sectors λ is a state (where λ is now the distribution of sectors over markups). To make this problem tractable I follow the lead of Krusell and Smith (1998). Since I already need to specify a price function for μ, a convenient choice of moment to characterize λ is last period's aggregate markup, μ_{-1}. I use the approximate law of motion

$$\log \mu = \beta_0 + \beta_1 \log \mu_{-1} + \beta_2 \log g.$$

More details on the solution of the firm problem and equilibrium can be found in Appendix B.

3.7 Comments on assumptions

CES demand structure An alternative formulation of the demand system could have been chosen. A pertinent example is nested logit system commonly used in structural estimation of demand elasticities.[22] However, as shown by Anderson, de Palma, and Thisse (1992), the nested CES structure is isomorphic to a nested logit with a population of heterogeneous consumers that each choose a single option at each stage.[23] That is, consumers may, on average equally prefer Kraft mayonnaise and Hellman's, while *iid* taste shocks push each consumer's tastes towards one or the other each period. Once aggregated a CES structure with equal weights is consistent with these preferences.[24]

[22] For estimation on the same kind of data used in this paper see: Lein and Beck (2015) (nested logit), Dossche, Heylen, and den Poel (2010) (AIDS), Hottman, Redding, and Weinstein (2014) (nested CES).

[23] I thank Colin Hottman for making this point, which is also made in the same way as above in Hottman (2016).

[24] This is also a useful way of thinking about multi-product firms. Continuing with the mayonnaise example, Kraft and Hellmans sell many different varieties of mayonnaise. However in the eyes of each consumer, these varieties are not necessarily substitutable. To take a simple example, both sell a standard and a low fat variety. If customers view standard / low fat as perfect substitutes but are heterogeneous in these preferences then *within* Kraft there is no substitutability between standard / low fat. But there is substitutability for some consumers *between* Kraft and Hellmans low fat mayonnaise. These preferences could be aggregated into a CES aggregator of bundles of the firm's goods.

Random menu costs Random menu costs serve two purposes in the model. First, they generate some small price changes. Some firms, having recently changed their price and accumulating little change in sectoral productivity, draw a small menu cost and again adjust their price. As we will see, a monopolistically competitive model with random menu costs gives distribution of price changes that appear as smoothed versions of bimodal spikes of Golosov and Lucas (2007).[25]

Second, and most importantly, random menu costs that are private information allows me to avoid solving for mixed-strategy equilibria. A technique I borrow from Doraszelski and Sattherwaite (2007). One could imagine solving the model under mixed strategies with fixed menu costs. Given the values of adjustment and non-adjustment and a fixed menu cost ξ, the firm may choose its probability of adjustment

$$\gamma_i(s,\mathbf{S}) = \arg\max_{\gamma_i \in [0,1]} \gamma_i \left[v_i^{adj}(s,\mathbf{S}) - \xi \right] + (1-\gamma_i)\, v_i^{stay}(s,\mathbf{S}).$$

If firm $-i$ is choosing a mixed strategy such that $v_i^{adj}(s,\mathbf{S}) - \xi = v_i^{stay}(s,\mathbf{S})$, then a mixed strategy is weakly a best-response of firm i. If one believes that menu costs are fixed, then this provides an alternative rationale for small price changes. Some firms may not wish to adjust prices this period, yet their mixed strategy over adjustment leads them to change prices nonetheless. However the solution of this model would be vastly more complicated.

Information I assume that the evolution of product quality within the sector (z_{1j}, z_{2j}) is known by both firms at the beginning of the period and only menu costs are private information. An arguably more realistic case, is that menu costs are fixed but firms know only their own productivity and past prices of both firms. This would add significant complexity to the problem. First, if productivity is persistent then firms' would face a filtering problem and a state vector that includes a prior over their competitor's productivity. Second, computation is still complex even if productivity is *iid*. From firm one's perspective z_{2j} would be given by

[25] Midrigan (2011) explicitly models multi-product firms and shows that the implications for aggregate price and quantity dynamics are—when calibrated to the same price-change data—the same as a model with random menu costs. What is important for these dynamics is that the model generates small price changes, leading the author to state that *"the conclusions that I draw are not sensitive to the exact mechanism I use to generate small price changes."* In this sense one can think of the random menu costs in my model standing in for an un-modelled multi-product pricing problem.

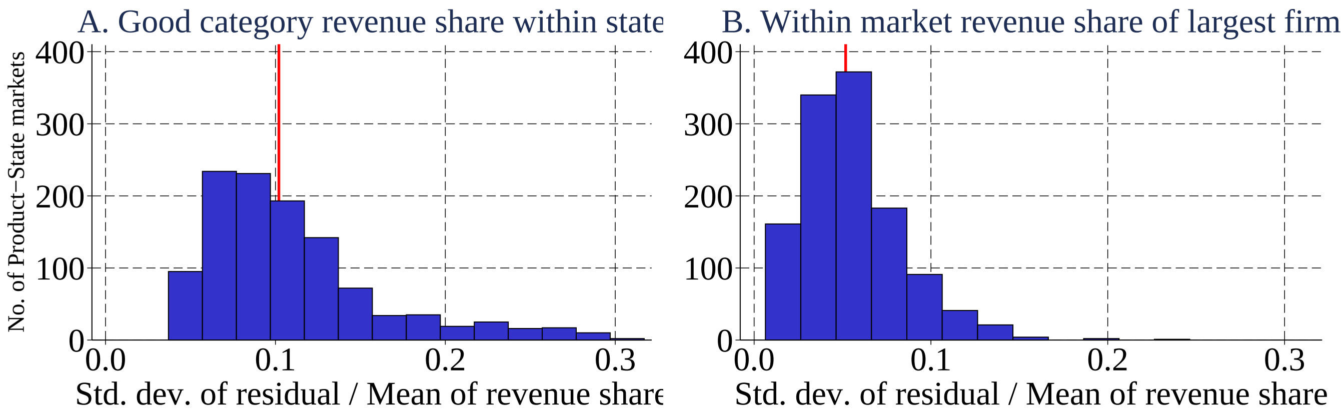

Figure 2: Sources of fluctuations in revenue shares: Across vs. Within sectors

Panel A. Histogram is of x_{ps} at the product p state s market level, where x_{ps} is constructed as follows. First, for each product-state pair, a cubic trend is fitted to the time-series of the share of product category revenue in total state revenue: $rshare_{pst} = r_{pst} / \sum_p r_{pst}$. Second, a time-series of residuals e_{pst} is computed by $e_{pst} = rshare_{pst} - \widehat{rshare}_{pst}$. The measure x_ps is then equal to the time-series standard deviation of e_{pst} divided by the mean of $rshare_{pst}$. **Panel B.** Follows identically, except that the relevant revenue share is the within market revenue share of the largest firm: $rshare^{top}_{pst} = \max_i \{r_{ipst}\} / \sum_i r_{ipst}$.

some known distribution, which firm one must integrate over when computing payoffs because (i) z_{2j} directly enters firm one's payoffs through the sectoral price index, (ii) z_{2j} indirectly enters firm one's payoffs through the price adjustment policies of firm two which depend on its productivity. Integrating over these functions would be computationally costly.

Correlation of productivity shocks I assume that innovations to the firm level demand shifter z_{ij} are independent across firms. In reality a component of shocks at the firm level will be correlated across firms within the sector.

We can get a sense of whether this is a good assumption by turning to the data. In the case that all shocks are at the firm level, revenue shares of each product category would be constant over time within each geographic market. In the case that all shocks are at the sectoral level, revenue shares of each product category would fluctuate over time, but the revenue shares of firms within each market would be stable. To get a sense of which case is prevalent Figure 2 plots histograms of the relative volatility of (a) a product category's share of total state-quarter spending, (b) the within product category revenue share of the largest firm. The measure is the standard deviation relative to a cubic time trend. If sector- (firm-) level shocks dominate, then we would expect larger numbers in panel A (B). The distributions are similar, which suggests that the underlying shocks are roughly half sectoral and half firm level. Motivated by this, forthcoming robustness checks of my results will consider the case that the shocks faced by the firm also contain a sectoral component.[26]

4 Comparing market structures - Illustrative

To understand the dynamics of markups in the two models I consider a simple exercise which corresponds to the central experiment in Golosov and Lucas (2007). Aggregate shocks are shut down and I examine the response of markups following a one time unforeseen increase in money. Firms assume that the aggregate markup remains at its steady state level.[27] Both models are studied at the parameter values which I estimate in the following section.

Market structure - Monpolistic competition

Figure 3 describes the behavior of firms in the monopolistically competitive model. The red (green) lines describe a firm that has received a string of positive (negative) quality shocks. The thin lines in panel A plot the evolution of each firm's markup absent the increase in money supply, and the thin lines in panel B plot the firm's probability of adjustment $\gamma_i(\mu_i)$. The dashed lines in panel A describe the optimal reset markup of each firm $\mu_i'(\mu_i)$. I assume that both firms draw sequences of large menu costs, so that their prices do not adjust, and since this is the monopolistically competitive model these firms are independent.

Now consider the thick lines in Figure 3 which describe behavior under a permanent increase in the money supply in period 40 which, absent adjustment, reduces both firms markups. The low markup firm's probability of adjustment increases as its markup moves away from its reset value. The size of its optimal adjustment now accommodates the entire increase in nominal costs, so increases by precisely the size of the shock. At the high markup firm, the shock

[26]It should become clear that this is not straight-forward. Although adding sectoral shocks to the duopoly model is simple, adding them to the monopolistically competitive model—to which I aim to compare the duopoly model—is not. With sectoral shocks, each sector in a monopolistically competitive model will be different over time, drastically complicating the computation of the equilibrium.

[27]This turns out to be a good approximation since the aggregate markup does not enter the static first order condition of the firm. In the monopolistically competitive model this is formalized by Proposition 7 of Alvarez and Lippi (2014). The explanation for this is that, as noted previously, the aggregate markup has only a second order effect on the policies of the firm.

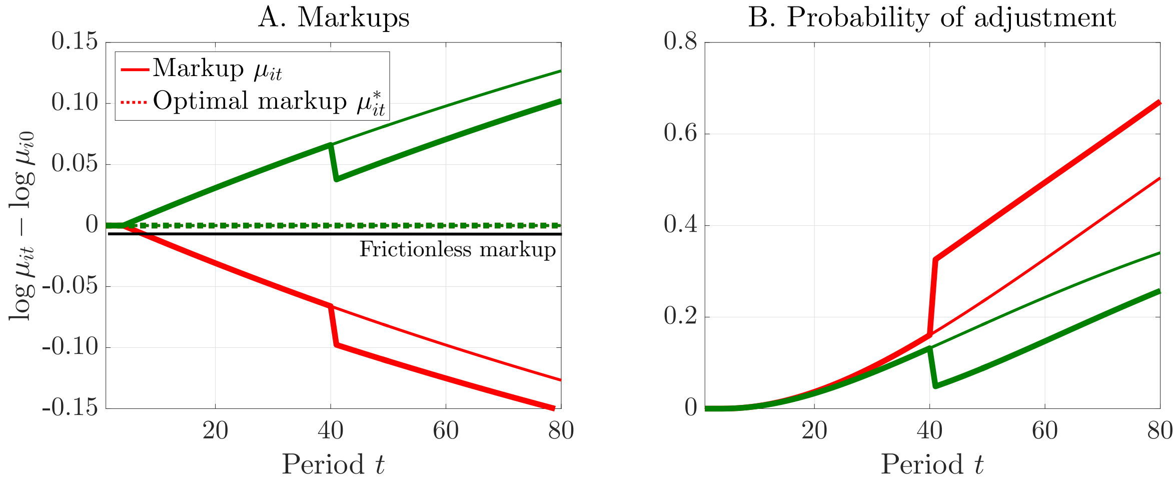

Figure 3: Example - Positive monetary shock in Monopolistically competitive model

Notes Thin solid lines give exogenous evolution of markups for two firms absent a monetary shock. Thin dashed lines give corresponding optimal markups conditional on adjustment $\mu'_1 = \mu^*$ and $\mu'_2 = \mu^*$. Thick solid lines include a monetary shock in period 40 which decreases both firms' markups. Thick dashed lines (which lie on top of the thin dashed lines) give the corresponding optimal markups. The model solution is solved in steady state and the monetary shock is a one-time unforeseen level increase in money. The y-axis in Panel A describes the log deviation of markups from the value chosen when shocks and menu costs are zero, $\bar{\mu} = 1.31$.

moves it closer to its reset value, its probability of adjustment falls, and its size of adjustment falls by the size of the shock. Note that the firms' optimal markups are equal and unaffected by the shock.

This behavior curtails the real effects of the monetary expansion. The distribution of adjusting firms shifts towards those with already low prices. These are firms that are increasing their prices and now by larger amounts. Neutrality of money is due to the behavior of these firms with low markups and a high probability of adjustment that are *marginal* with respect to the shock.

Market structure - Duopoly

Figure 4 repeats this exercise in the duopoly model. A crucial departure from Figure 4 is that I now consider two firms that are in the same sector. The firms differ both in their policies absent the shock, and in their response to the shock. These differences driven by the interaction of menu costs and the within sector strategic complementarities that arise in the duopoly model.

Strategic complementarity Formally, strategic complementarity means that the cross-partial derivative of a firms profit function is positive ($\pi_{12} > 0$): if firm two's price is high, then firm one also desires a high price. Economically, this is the case for two reasons: (i) the household has a lower ability to substitute across, than within sectors, (ii) each firm is non-atomistic and understands how its price moves the sectoral price. If firm two's price is high, then high within sector substitutability means that firm one can post a price not much lower than its competitor and achieve a high market share. Because of (ii) the firm knows that increasing its price also increases the sectoral price. This dampens the increase in its relative price within the sector, while low substitutability across sectors leads to a small impact on sectoral demand. Since $\eta > \theta$, then the first effect dominates. If (ii) did not hold, and the firm were mistakenly atomistic, then its optimal price would—like the monopolistically competitive firm—be independent of the other price(s) in its sector.

In Appendix C I make precise these strategic complementarities in the duopoly model under CES preferences. I show that strategic complementarities imply that the best response functions $\mu_i'(\mu_j)$ in a frictionless economy (the solution of the static Bertrand-Nash equilibrium when $\bar{\xi} = 0$) are upward sloping with a slope less than one: if μ_j is greater than the frictionless Nash μ^*, then the best response is to undercut with $\mu_i^* \in (\mu^*, \mu_j)$. Figure E1 panel B, plots best responses for the calibrated parameters of the model and comparative statics with respect to η. When η is higher, the frictionless markup is lower but the firm has less of an incentive to undercut its competitor's price since a price slightly lower than its competitor will lead to a large shift in demand. That is, strategic complementarities are increasing in η, and best response functions are steeper. As η declines to θ, strategic complementarities become zero and the best-response function becomes horizontal: mathematically, the sectoral markup drops out of the firm's profit function.

Policy functions without the shock The first notable departure from the monopolistically competitive model is in the markup policies of the two firms. In particular, the optimal markups $\mu_i'(\mu_i, \mu_j)$ are no longer equal. In response to its competitor having a high markup and the strategic complementarities in pricing, the low markup firm would reset its markup to below, but near, its competitor. This serves three purposes. First, choosing a higher reset markup encourages the high markup firm to not undercut the low markup firm: in the short run the

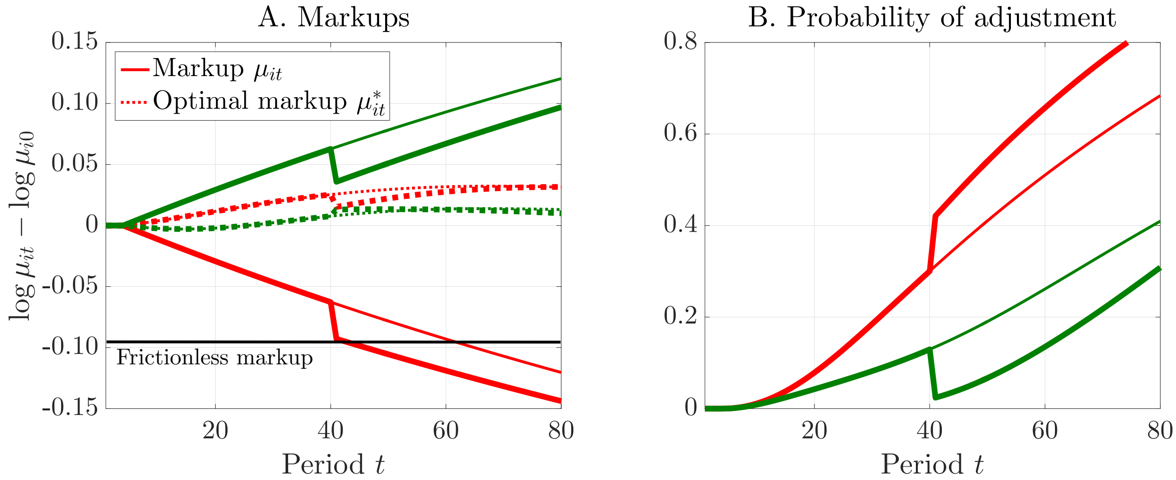

Figure 4: Example - Positive monetary shock in Duopoly competitive model

Notes Thin solid lines give exogenous evolution of markups for two firms *within the same sector* absent a monetary shock. Thin dashed lines give corresponding optimal markups conditional on adjustment $\mu_1'(\mu_1, \mu_2)$ and $\mu_2'(\mu_1, \mu_2)$. Thick solid lines include a monetary shock in period 40 which decreases both firms' markups. Thick dashed lines (which lie on top of the thin dashed lines) give the corresponding optimal markups. The model solution is solved in steady state and the monetary shock is a one-time unforeseen level increase in money. The y-axis in Panel A describes the log deviation of markups from the value chosen when shocks and menu costs are zero, $\bar{\mu} = 1.31$.

policy maintains market share. Second, when it does adjust its price, the high markup firm's best response will also be high: in the long run the policy maintains a high average markup. Third, slightly undercutting its competitor delivers market share while menu costs reduce the likelihood of being undercut in future periods. The low markup firm chooses a 'wedge' in markups that has some short-run persistence.

In a frictionless economy, the high markup firm would have a best response which would be to undercut the low markup firm. The fact that the low markup firm has a high reset price reduces the second order gains associated with an 'undercut' strategy to less than the menu cost. In this way the menu cost grants firms with high prices some short run commitment to not undercut and the high reset price of the low markup firm props up a high sectoral price.[28]

The outcome of these non-cooperative policies, is that the firms achieve markups substantially above the frictionless Bertrand-Nash equilibrium. The size of this wedge is bounded by

[28]Another way to think about this is as follows. Suppose that the low priced firm's markup was below the average markup. Then for the average markup to be the average markup it must be that high markup firms adjust to a price above the average markup. This is not an equilibrium of the model, since the high markup firm's dynamic best response would be a price lower than its competitor. In this way the 'cycles' visible in Figure 4A maintain the average markup.

the size of the menu cost. Markups that are *too high* invite deviations that increase firm values that exceed the menu cost. I return to quantify this wedge and its implication for welfare in Section 6. Appendix D considers a static game that further strengthens this intuition for the role of menu costs in delivering high markups.

Policies following the shock The second difference is in the response to the monetary shock. The desired price increase at the marginal firm still jumps to cover the increasing nominal wage, but this is tempered by the fall in its competitor's real price. Since prices are strategic complements, a falling real price at its direct competitor reduces the optimal price of the low markup firm. The low markup firm's demand elasticity has increased as its sector has become exogenously more competitive. This increase in demand elasticity also reduces the marginal value of any price increase. Integrated over the desired price increase, this tempers the jump in the probability of price adjustment.[29] In this example, the frequency and size of price adjustment at the marginal firm increase by half as much as they do in the monopolistically competitive model.

The above logic assumes that the high markup firm's nominal price remains fixed following the shock. This is a fairly good approximation for three reasons. First, the high markup firm's real price has moved closer to its reset price, lowering its probability of adjustment. Second, the randomness of the menu cost means that although it knows that its competitor's price has a

[29]Given a fixed price of firm j, we can use the Fundamental Theorem of Calculus to express the change in value delivered by some desired price increase of firm i as

$$\Delta_i = v_i(\mu_i^*, \mu_j) - v_i(\mu_i, \mu_j) = \int_{\mu_i}^{\mu_i^*} \frac{\partial v_i\,(u, \mu_j)}{\partial u} du.$$

Due to strategic complementarities, (i) the derivative is positive for $\mu_i < \mu_j$, which is the case under consideration, (ii) the fall in μ_j reduces the value of the derivative. A decline in μ_j, gives a smaller derivative integrated over a smaller support since the size of price change, $\mu_i^* - \mu_i$, also decreases. In this way a decline in μ_j lowers the value of adjustment. Assuming that μ_i^* is a function of just μ_j, then we can write this change of value as a function of just μ_j: $\Delta(\mu_j)$. The derivative of this function, by Liebniz's rule, is

$$\Delta_i'(\mu_j) = \frac{\partial \mu_i^*\,(\mu_j)}{\partial \mu_j} \left(\left. \frac{\partial v_i\,(u, \mu_j)}{\partial u} \right|_{u=\mu_i^*(\mu_j)} \right) + \int_{\mu_i}^{\mu_i^*(\mu_j)} \frac{\partial^2 v_i\,(u, \mu_j)}{\partial u \partial \mu_j} du.$$

Both components of the first term are positive. The first because of strategic complementarities, the second because we are considering a firm with an optimal price increase, which implies v_i is increasing in μ_i. The second term is positive because of strategic complementarity.

high probability of increasing, the high markup firm does not know for sure that it will. In the case that it increases its reset markup and its competitor remains fixed then it further loses market share in the short run. Third, even if the high markup firm could better coordinate its price change, it would not want to significantly increase its reset markup. The level of markups that firms can sustain—above the frictionless markup—are constrained by the menu cost. The menu cost can only wipe out small surpluses from undercutting a competitor and these get larger the higher initial markups are. Despite this, we do see a small increase in the optimal markup of the high markup firm, encouraging its competitor to choose a higher price conditional on adjustment.

This analysis shows that a key point to understanding monetary non-neutrality in the duopoly model is the following: *The behavior of the marginal firm, is now affected by its inframarginal competitor*. These figures give a particularly stark example using with markups below and above their reset markups. Later I will argue that this is the quantitatively relevant case in generating larger real effects in the duopoly model. If both markups are initially low, then the firms respond similarly to two unrelated low markup firms in the monopolistically competitive model. If both markups are initially inframarginal, then, like two inframarginal firms in the monopolistically competitive model, the firms do not respond.

Negative monetary shock Finally, for the sake of repetition and completeness, consider the symmetric case of a negative shock to the money supply. In this case, nominal wages fall, increasing markups conditional on non-adjustment. The inframarginal firm is now the high markup firm who is considering decreasing their price while the shock is making their competitor less competitive. With their competitor's markup increasing the desired size of price decrease is cushioned and the firm's demand elasticity falls, reducing the value of a price decrease. Again, the frequency and size of price change increases by less at the firms that are marginal to the aggregate shock.

In these examples firms are not correctly forecasting the aggregate markup and—for illustrative purposes—the shock in period forty is extremely large. Moreover the monetary shock was an unforeseen and permanent rather than an understood part of the economic environment and persistent. I now return to the full model for a quantitative comparison of monetary non-neutrality under both market structures.

5 Calibration

In this section I calibrate both models to a standard set of good-level pricing moments considered in the quantitative menu cost model literature. Section 6 gives the main results regarding aggregate dynamics and examines the intuition from the previous section. Section 7 discusses additional results which relate to how menu costs induce allow duopolists to sustain a wedge between average and frictionless markups and endogenous price rigidity in the duopoly model.

Externally fixed parameters

Both models are calibrated at a monthly frequency with $\beta = 0.95^{1/12}$. I follow the same procedure as Midrigan (2011) for calibrating the persistence and size of shocks to the growth rate of money: $\rho_g = 0.61$, $\sigma_g = 0.0019$.[30] I set $\bar{g}$ such that the model generates annual inflation of 2 percent. The final parameter set externally is the cross-sector elasticity θ which I set to 1.5, in the range of those estimates from micro-econometric studies of grocery store data (Dossche, Heylen, and den Poel, 2010).

Internally estimated

The remaining parameters in both models are (i) the within-sector elasticity of substitution η, (ii) the size of shocks to z denoted σ_z, (iii) the distribution of menu costs. I assume menu costs are uniformly distributed $\xi \sim U\left[0, \bar{\xi}\right]$ and refer to the parameter $\bar{\xi}$ as the menu cost. In choosing these parameters the moments I match are the average absolute size and frequency of price change in the IRI data, as well as a measure of the average markup.

As shown by Golosov and Lucas (2007), matching these first two moments severely constrains the ability of the monopolistically competitive menu cost model to generate sizeable output fluctuations. A high size of price change implies low markup firms adjusting following a monetary shock will have larger positive price changes. A high frequency of price change means the increase in nominal cost is more quickly incorporated into the aggregate price index. The average absolute log size of price change is 0.10, the average frequency of price change is

[30] Specifically, I take monthly time-series for $M1$ and regress $\Delta \log M1_t$ on current and 24 lagged values of the monetary shock series constructed by Romer and Romer (2004). I then estimate an AR(1) process on the $\Delta \widehat{\log M1_t}$ predicted values from this regression. The coefficient on lagged money growth is $\rho_g = 0.608$, with standard error 0.045. The standard deviation of residuals from this second regression gives σ_g.

0.13. Appendix A details the construction of these measures. Here I simply note that I exclude sales and small price changes that may be deemed measurement error.

The third moment, the average markup, is motivated two ways. First, note that if the within-sector elasticity was the same in both models, then the effective elasticity of demand faced by the duopolist would be lower. The duopolist is non-atomistic with respect to its price taking behavior when it comes to the sectoral markup. Since the cross-sector elasticity $\theta < \eta$, then the effective elasticity of the duopolist lies between θ and η. A lower demand elasticity leads to lower price flexibility. Calibrating to the average markup means the elasticity of demand faced by firms in both models are approximately the same. In the following section I show that the main result of higher aggregate price stickiness under duopoly is robust to the value of η chosen in the monopolistically competitive model.

Second, matching the average markup implies that the average rate of profits are the same in both models. A ranking of estimated menu costs is therefore preserved when transformed into the ratio of menu costs to profits, which is an economically more meaningful measure. Bearing this in mind will allow me to make statements regarding the firm-level price stickiness endogenously generated by each model by simply comparing the estimated menu costs. It will turn out that the duopoly model does generate endogenously stickier prices with respect to firm-level shocks. Calibrating both models to match the same frequency of price change means that this feature will not play a direct role in a comparison of aggregate dynamics.

I choose a value of the average markup of 1.30. In their estimation of markups across 50 sectors Christopoulou and Vermeulen (2008) find an average markup in the US of 1.32. The average markup estimated by Berry et al. (1995) for the US auto industry is 1.31. The average markups estimated by Hottman (2016) using retail goods are in the range of 0.29 to 0.33. For comparison with macro models, a markup of 1.30 would be chosen by a monopolistically competitive firm—absent frictions—facing an elasticity of demand of 4.33. This is a little low with respect to values chosen in macroeconomic models, but is in line with recent elasticity estimates for grocery goods from Beck and Lein (2015), Dossche, Heylen, and den Poel (2010) and Hottman, Redding, and Weinstein (2014). Since measures of average markups span a large range in the literature, Section 6.4 discusses robustness of my results to this choice of average markup.

Calibrated parameter values are given in Table 1. The baseline calibration of the monopolis-

		Duopoly	Monopolistic competition			
			Base	Alt. I	Alt. II	Alt. III
A. Parameter						
Elasticity of demand	η	**10.5**	4.5	**10.5**	**10.5**	**6**
Size of menu cost	$\bar{\xi}$	**0.17**	0.21	**0.17**	0.42	0.29
Size of shocks	σ_z	**0.04**	0.04	**0.04**	0.04	0.04
B. Moments matched						
Average markup	$\mathbb{E}\left[\mu_{it}\right]$	**1.30**	**1.30**	1.12	1.13	1.22
Frequency of price change		**0.13**	**0.13**	0.19	**0.13**	**0.13**
Size of price change		**0.10**	**0.10**	0.05	**0.10**	**0.10**
C. Results						
Std. deviation consumption	$\sigma(C_t)$	0.31	0.13	0.06	0.13	0.13
Average - Frictionless markup	$\mathbb{E}\left[\mu_{it}\right] - \mu^*$	0.10	0.02	0.01	0.02	0.02

Table 1: Parameters in monopolistically competitive and duopoly models

tically competitive model is given by the column *Base*. The remaining columns give alternative calibrations of the monopolistically competitive model, which I will use to describe other results in the following sections.

For now, compare the *Base* calibration to *Alt I* which takes the monopolistically competitive model at exactly the same parameters as those calibrated in the duopoly model. The *Base* calibration calls for a lower elasticity of substitution and higher menu cost to match the same moments. With a higher elasticity and lower menu cost *Alt I* generates a substantially higher frequency of price change and smaller average size. With more flexible firm-level prices, output fluctuations—as measured by the standard deviation of consumption $\sigma(C_t)$—are less than half the size of *Base*.[31] This comparison serves to show that my calibration strategy is designed to undo features of the models that would lead to larger real effects in the duopoly model were one not to match these facts.

[31] The standard deviation of log deviations of consumption from steady-state is a common summary statistic for the real effects of shocks to the money supply in menu cost models cited in Section 2. Specifically $\sigma(C_t)$ is equal to the standard deviation of HP-filtered deviations of log of consumption from its steady state value—its value in an economy where $g_t = \bar{g}$.

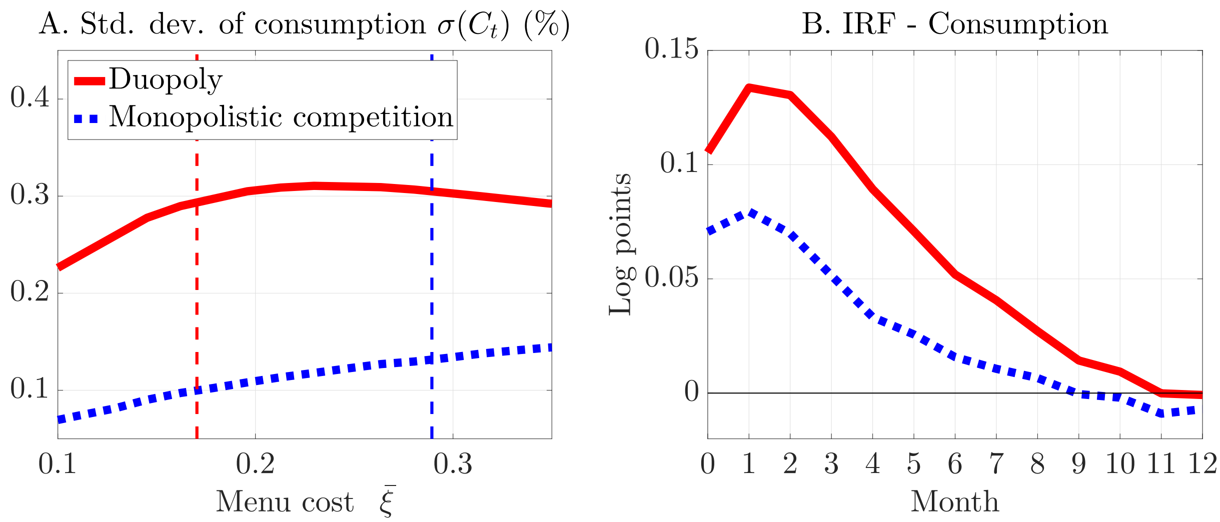

Figure 5: Monetary non-neutrality in the duopoly and monopolistically competitive models

Panel A. In both cases the size of shocks to demand and elasticity of demand are as in Table 1. **Panel B.** Impulse response function computed by local projection, see footnote 33.

6 Aggregate dynamics

In this section I (i) present the main result comparing monetary non-neutrality in both models, (ii) verify the quantitative relevance of the mechanism just described, (ii) consider the robustness of this result, and (iii) further distinguish the mechanism from existing methods for generating larger real effects of monetary shocks in menu cost models.

6.1 Result

Table 1 also delivers the main result of the paper, which is that fluctuations in output are around 2.5 larger in the duopoly model (0.314 vs 0.126).[32] Figure 5 expands on these results. Panel A gives the comparative statics of $\sigma(C_t)$ with respect to the menu cost, with the calibrated values of the menu cost given by the vertical dashed lines. An alternative measure of monetary non-neutrality is the cumulative response of consumption, measured as the area under the impulse response function of consumption with respect to shocks to the monetary growth rate. Panel B plots this IRF computed via a local projection approach for both models. The cumulative

[32]The random menu costs also imply that the monopolistically competitive model in this paper generates larger output fluctuations than the fixed menu cost Golosov-Lucas model calibrated to the same data. In that model I find that $\sigma(C_t) = 0.08$. This is for the same reason as in Midrigan (2011), random menu costs generate some small price changes.

response is twice as large in the duopoly model.[33]

These result can be compared with other papers that seek to address the monetary neutrality of the Golosov and Lucas (2007) model. Output fluctuations are slightly larger than in Midrigan's (2011) multi-product firm model ($\sigma(C_t) = 0.29$). The amplification when moving from monopolistic competition to duopoly is also slightly larger than Nakamura and Steinsson (2010) find when comparing their single and multi-sector models (a ratio of 1.82). In this sense, this paper adds realism—markets are concentrated—and moves the models towards the large real effects of monetary shocks we find in the data.

6.2 Verifying the mechanism

To check whether the intuition from Section 4 holds in the full model we can study the response of the size and frequency of price change for low and high markup firms following a positive monetary shock. Figure 6 shows that the intuition of Figures 3 and 4 carries over exactly. Low and high markup firms in the duopoly model (solid lines) are defined sector by sector. In the monopolistically competitive model (dashed lines) I pair random firms and assign them to the low and high categories according to their markups. Both the frequency and size of price change of low markup firms respond by less in the duopoly model. The monetary shock lowers the markups of inframarginal high markup firms which reduces marginal firm's value of a price increase and also the optimal price conditional on adjustment.

Reassuringly, the size of price change at high markup firms falls by less in duopoly model. This is consistent with high priced firms maintaining a high markup given the jump in probability of price increase at their competitor. It is also a force towards greater aggregate price

[33] The local projection IRFs that I compute here and throughout this section are econometrically equivalent to the approach used by Jorda (2005). To the best of my knowledge this paper is the first to use them in the quantification of a heterogeneous firms model so I discuss their construction briefly. The economy is simulated for 5,000 periods with aggregate and idiosyncratic shocks. Given the known time-series of aggregate shocks to money growth ε_t^g, then the horizon τ IRF is $IRF_\tau = \sum_{s=0}^{\tau} \hat{\beta}_\tau$, where $\hat{\beta}_\tau$ is estimated from

$$\Delta \log C_t = \alpha + \beta_\tau \varepsilon^g_{t-\tau} + \eta_t.$$

The benefits of computing the IRF in this manner are (i) it is exactly what one would compute in the data if the realized path of monetary shocks was known, which is consistent with the approach that uses identified monetary shocks from either a narrative or high-frequency approach (Gertler and Karadi, 2015), (ii) it avoids the time consuming approach of simulating the model many times as is usually done in heterogeneous agents models with aggregate shocks.

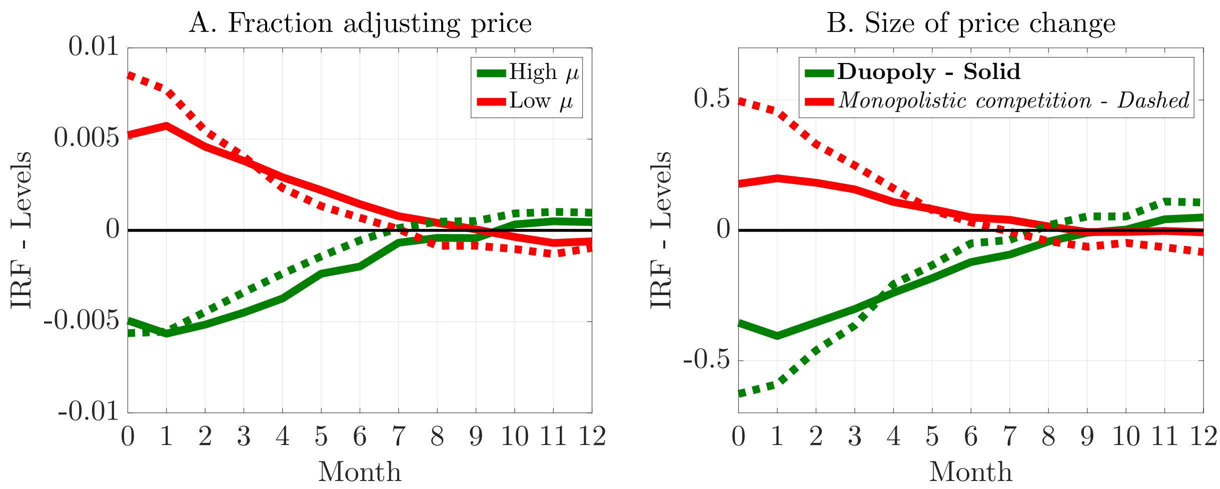

Figure 6: Impulse responses to a positive monetary shock

Notes Impulse response functions are computed by local projection. For details see footnote 33. To isolate the effect of a positive monetary shock, only positive innovations to money growth $\varepsilon_t^g > 0$ are included in the regressions used to compute the impulse response function. Green (Red) lines correspond to High (Low) markup firms. Solid (Dashed) lines correspond to the Duopoly (Monopolistically competitive) model.

flexibility in the duopoly model: high priced firms decrease their prices by less. However the probability of adjustment falls at high markup firms, implying that this differential response in terms of the size of price decrease does not have large effects.

6.3 Decomposition

I can more formally decompose the response of the economy by considering a decomposition of movements in the aggregate price index into its extensive and intensive margin. This follows the spirit of Caballero and Engel (2007)'s theoretical decomposition of a wide class of sticky price models.

- *To be added. See summary in introduction and slides.*

6.4 Robustness

This main result depends on the fact that firms can choose when to change their prices, but is not affected by alternative calibration strategies for the elasticity of demand.

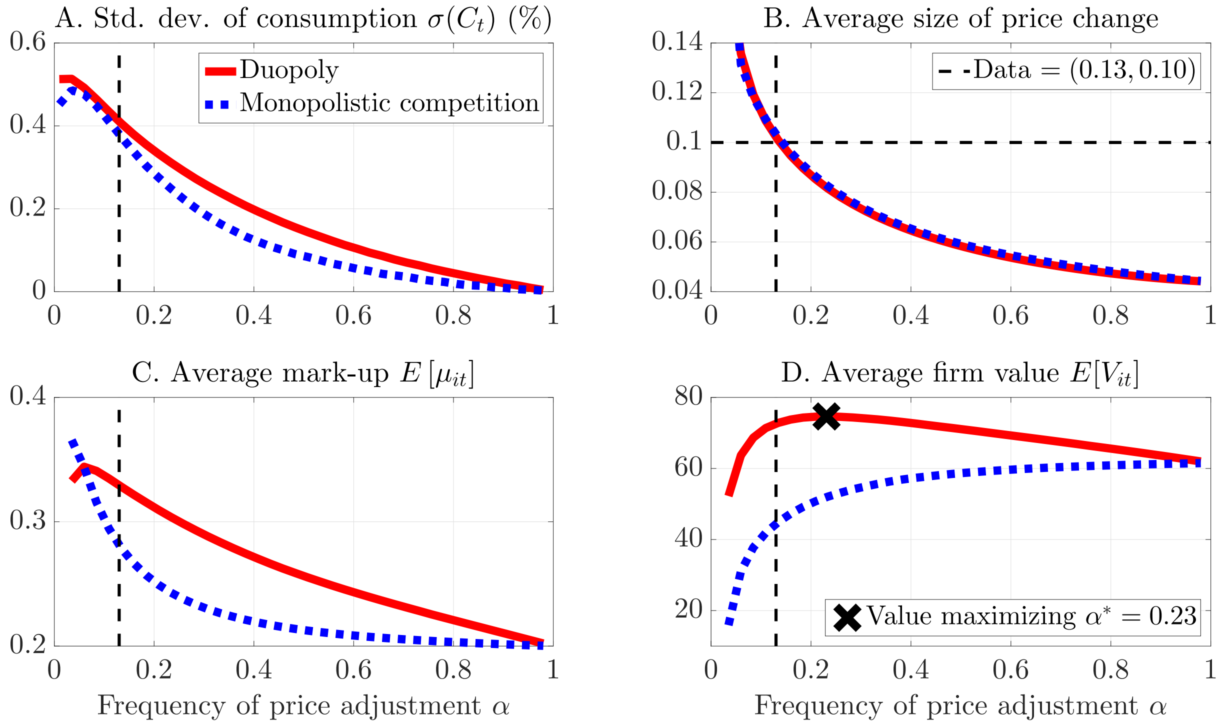

Figure 7: Results from the Calvo model for varying degrees of nominal rigidity

Notes The vertical black dashed line in each plot marks the empirical frequency of price adjustment $\alpha = 0.13$. In both duopoly and monopolistically competitive models the size of shocks σ_z is set to 0.05 in order to match the average size of price changes at $\alpha = 0.13$ (panel B). In both models $\theta = 1.5$ and the elasticity of demand is chosen to give a frictionless markup of 1.20.

State vs. time dependent price setting

A motivation for studying state-dependent menu cost models of price adjustment is that they realistically allow firms to choose when to change their prices, as opposed to time-dependent Calvo models of price adjustment which assume that adjusting firms are randomly chosen. Comparing the monopolistically competitive menu cost model in this paper to its Calvo counterpart, parameterized to match the same set of moments, I find that $\sigma(C_t)$ is three times larger in the Calvo model (0.38 vs. 0.13).[34] However, Figure 7A shows that when comparing monopolistic competition to duopoly *within* the Calvo model—again recalibrating the size of shocks (panel B)—output fluctuations are only 10 percent larger in the duopoly model (0.41 vs 0.38).

[34] In this sense the duopoly model model accounts for around three quarters of the difference between monopolistically competitive time and state-dependent models. This comparison may seem misplaced. However, a feature of the literature has been to ask whether menu-cost models can deliver real effects as large as Calvo models. In Midrigan (2011) the main result is that a Golosov-Lucas model delivers $\sigma(C_t) = 0.07$, a Calvo model $\sigma(C_t) = 0.35$, and his benchmark multi-product model $\sigma(C_t) = 0.29$. The result being that his model generates real effects of money that are 80% as large as in the Calvo model. In my case this number is a little more than 80%.

Compare this to the main result in Section 6: output fluctuations were more than twice as large in the duopoly model.[35]

Why, in the Calvo model, are the real effects of monetary shocks similar across market structures? In a Calvo setting, the size effect is still present: following a positive monetary shock, the falling real prices of competitors will reduce the optimal price of low markup firms that increase their nominal price. However the frequency effect is no longer present. Although the value of a price change falls, this does not change the extensive margin behavior of the firm in response to the shock, since the opportunity to adjust is random. That the amplification is small shows that the frequency effect is the dominant force behind the larger real effects of monetary shocks in the duopoly menu cost model.

Calibration strategy for the elasticity of demand η

An alternative approach for calibrating the elasticity of demand would have been to choose η such that the effective elasticity of demand coincides exactly in the absence of menu costs. Appendix C derives the result that the frictionless markup in the duopoly model is

$$\mu_d^* = \frac{\varepsilon^*}{\varepsilon_d^* - 1} \qquad , \qquad \varepsilon_d^* = \frac{1}{2}\left(\eta + \theta\right),$$

such that the effective elasticity of demand is $6 = \frac{1}{2}(10.5 + 1.5)$. Column *Alt III* of Table 1 considers the monopolistically competitive model where $\eta = 6$, and the size of menu costs and shocks are again calibrated to match the same size and frequency of price change. With a higher elasticity than *Base*, prices far from their optimum are more costly to the firm, leading to more frequent price changes for any given level of menu cost. This requires a larger menu cost both in levels, and as a ratio of profits.[36] Once recalibrated, the model generates the same real output effects as *Base*. Column *Alt II* shows that the same is true if one takes $\eta = 10.5$ from the duopoly

[35]Figure 7 also shows that the alternative models of market structure behave in the same way as the nominal rigidity disappears. Again we get the result that as nominal rigidity increases (α decreases from 1), the value of the firm increases under duopoly and decreases in monopolistic competition. For purely technical reasons it is a challenge to solve the menu cost model with either very high or very low values of the menu cost due to issues relating to the approximation of the probability of price adjustment. Given this issue, the Calvo model is useful in that it can be studied better in these limiting cases.

[36]The size of shocks can be left the same. Increasing $\bar{\xi}$ lowers the frequency and increases the average size of price changes.

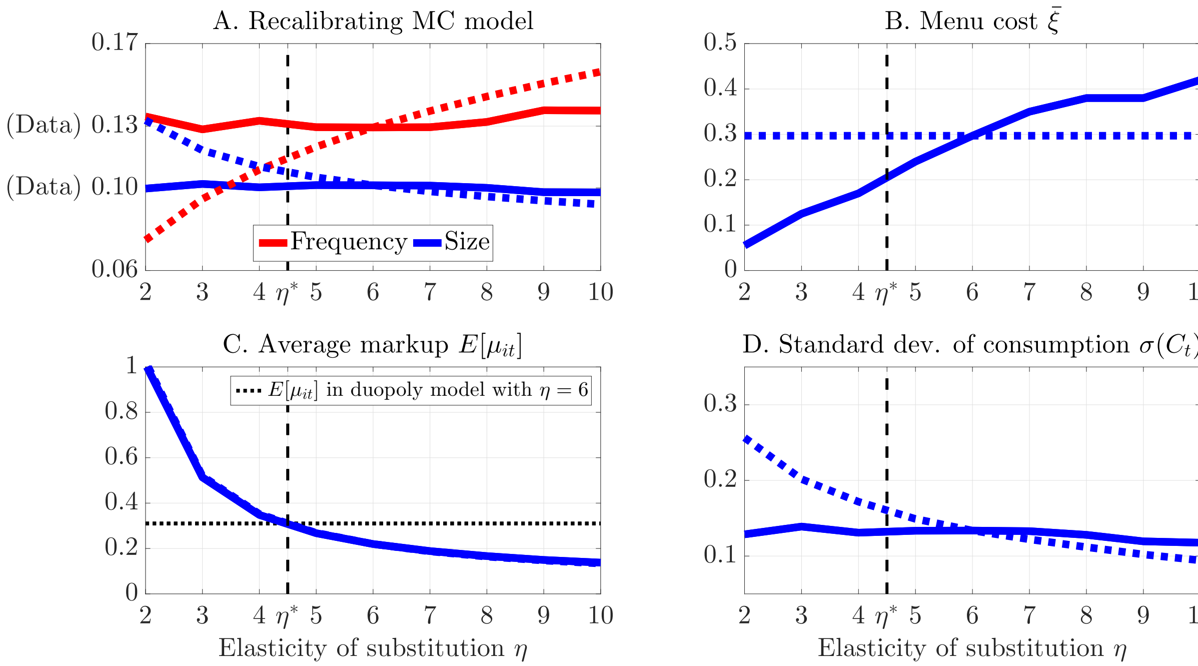

Figure 8: The effect of the elasticity of substitution in the monopolistically competitive model

Notes Solid lines denote values for the monopolistically competitive model under $\sigma_z = 0.04$ and values of $\bar{\xi}$ given in **Panel B**. The values of $\bar{\xi}$ are chosen to match the same data on frequency and size of price change, as shown in **Panel A**. Dashed lines correspond to the model where $\bar{\xi}$ is not recalibrated and is set to 0.297 as in Table 1. The vertical black lines mark the value of η^* which matches the same average markup as the duopoly model under $\eta = 6$, as shown in **Panel C**.

model and again recalibrates the size of menu costs.

Figure 8 shows that this holds across values of $\eta \in [2, 10]$ (or $\mu^* \in [1.11, 2.00]$). Solid lines describe the monopolistically competitive model under different values of η, each time recalibrating the size of the menu cost (panel B) to deliver the same size and frequency of price change (panel A). Dashed lines describe the same economy but with menu costs fixed at the baseline value of 0.29 from Table 1. In all cases $\sigma(C_t) \approx 0.13$. In this sense it does not matter which monopolistically competitive model—indexed by η— I compare the duopoly model to, so long as it is calibrated to match the size and frequency of price adjustment. It also means that larger real responses can not be generated by *'giving more market power to monopolistically competitive firms'* by reducing the substitutability of their goods.

The irrelevance of η for the aggregate dynamics of the monopolistically competitive model do not, however, carry over to the duopoly model. Recall that under a lower value of η, strategic complementarities are weaker and firms' static best response functions flatten. In the limit $\eta = \theta$, and the model becomes a model of monopolistic competition (the sectoral price index

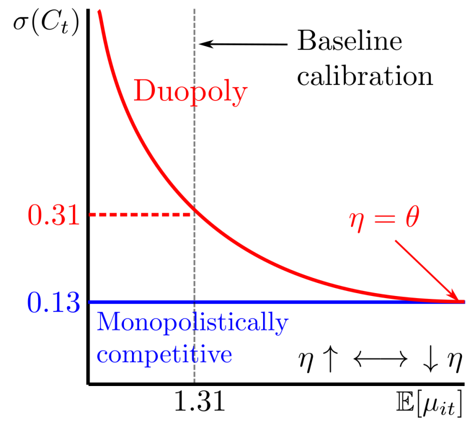

Figure 9: Monetary non-neutrality and the average markup

drops out of the firm's profit function). As per Figure 8D, under even very low η we would have $\sigma(C_t) = 0.13$. As η increases, strategic complementarities become stronger, increasing the real effects of money shocks. These comparative statics also change the average markup, which was used in the calibration. As η decreases (increases), the frictionless markup increases (decreases), pushing up (down) the average markup.

Figure 9 draws out this intuition. For a given average markup one would be able to determine the real effects of monetary shocks. In the monopolistically competitive model, the real effects of monetary shocks are independent of the average markup in recalibrated models. Due to the computational burden of recalibrating the duopoly model, robustness with respect to the average markup $\mathbb{E}[\mu_{it}]$ is forthcoming.

These results have an additional implication with regard to the macroeconomic importance of demand elasticity estimates from microeconomic studies. The macroeconomic implications of the monopolistically competitive model are, in a sense, misleadingly robust to market structure mis-specifciation. Once demand curves are log-linear, the slope is irrelevant for the macroeconomic implications of the model. If one accepts that market structure is important for macroeconomic dynamics, as this paper suggests, then this section further suggests that the parameter estimates governing the properties of markets are important. This may seem like an obvious statement: *If A is important, then the details of A are important*. But it is precisely the fact that the details are irrelevant under monopolistic competition that make this point interesting.

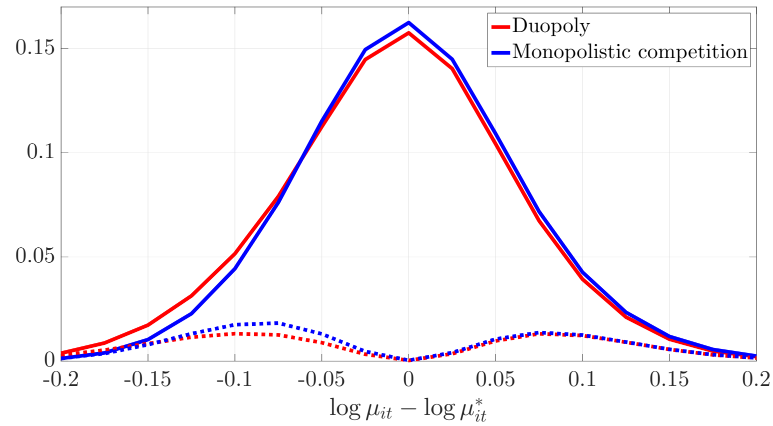

Figure 10: Distribution of markup gaps (solid) and markup changes (dashed) in the monopolistically competitive and duopoly models

6.5 Comparison to menu-cost models that amplify shocks

To further understand this result, I contrast the duopoly model to well understood extensions of the monopolistically competitive model. These extensions reduce monetary neutrality by altering the *microeconomics* of the model. In particular I want to assert that the mechanism in this paper does not work through (i) generating higher kurtosis in the distribution of desired price changes, (ii) generating strategic complementarities through the second-order properties of the firm demand function. Since the *macroeconomics* of the duopoly and monopolistically competitive model are the same, I do not compare the amplification here to models which alter the *macroeconomics* of the model to slow the pass-through of the monetary shock to movements in nominal cost.

Models of extra kurtosis

As discussed in Section 4, what is crucial for determining the size of the output response to a monetary shock is the shift in the mass of adjusting firms from high to low markup firms. In the case of an increase in the money supply this depends on the slope of the distribution of firms near the adjustment thresholds. In a model with Gaussian shocks, this slope is steep.

In a model with more small price changes, or more kurtosis in the distribution of price changes, this slope is shallower. In Midrigan (2011) and following work by Alvarez and Lippi (2014) this is achieved by modelling multi-product firms with economy of scope in price changes. Firms have n products and adjust all markups when one good hits a threshold of adjustment despite other goods' markups being close to their optimum. In Gertler and Leahy (2008) this is achieved through large infrequent shocks that throw μ_{it} beyond an adjustment threshold, forcing the firm to adjust while its markup is still not far from its reset value. Alvarez, LeBehin, and Lippi (2016) formalize these types of results by showing that—within this class of models—the frequency and kurtosis of price changes are sufficient statistics for the real effects of monetary shocks. If kurtosis is high then many price changes are interior to adjustment thresholds, which implies movements in adjustment thresholds sweep fewer firms into adjusting. The models of Gertler and Leahy (2008) and Midrigan (2011) deliver precisely this large kurtosis.

Figure 10 shows that the duopoly model is not a structural model that delivers extra kurtosis in the distribution of price changes relative to the baseline monopolistically competitive menu cost model. The distribution of desired price changes is similar in both models, with some additional left skewness under duopoly due to the lower frequency of price change at low markup firms. Moreover, both models were calibrated to the same frequency of adjustment. That the duopoly model generates larger real effects confirms that it does not belong to the class of models for which these sufficient statistics apply.

What differentiates the duopoly model from the class of models studied by Alvarez, LeBehin, and Lippi (2016) is the presence of strategic complementarities in price setting. The results from Alvarez and Lippi (2014) and Alvarez, LeBehin, and Lippi (2016) apply when—to a first order—a firm's optimal markup is independent of all other prices. Once strategic complementarities enter the model, this is no longer the case. In the duopoly model a competitor's price enters the first order conditions of the firm, breaking the application of these sufficient statistics. Similarly, models with strategic complementarities between the firm price and aggregate price, as will be discussed next, do not fit into the class of models studied in these papers.

An alternative model of strategic complementarity

As noted by Nakamura and Steinsson (2010), *"monetary economists have long relied heavily on strategic complementarity in price setting to amplify monetary non-neutrality generated by nominal rigidities"*. In monopolistically competitive models such strategic complementarities can be introduced between the firm's price and the aggregate price. A Kimball (1995) demand aggregator, as studied by Klenow and Willis (2016) and Beck and Lein (2015), can flexibly introduce such strategic complementarities. Demand curves feature an elasticity of demand which is increasing in a firm's relative price $\tilde{\mu}_{it} = (\mu_{it}/\mu_t)$.[37] Following a positive monetary shock, nominal rigidities lead μ_t to fall and marginal firms' relative prices increase. This reduces their desired size of price change and its value.[38]

Rather than supporting these *demand-side* real rigidities, the work of Klenow and Willis (2016) and Beck and Lein (2015) lead us to reject them. As Nakamura and Steinsson (2010) continue, *"introduction of such strategic complementarities render the models unable to match the average size of price changes for plausible parameter values...requir[ing] massive idiosyncratic shocks and large menu costs"*[39] The duopoly model features micro strategic complementarities, large amplification of monetary shocks, matches the same micro-data, and does so with (i) lower menu costs as a fraction of profits, (ii) the same size of idiosyncratic shocks. My results differ from the consensus that has formed, correctly, around competitive models. Why is this the case?

First, what are the quantitative problems with strategic complementarities in the monopolistically competitive model *a la* Kimball (1995)? The goal is to generate a pro-cyclical elasticity of demand: aggregate money increases, aggregate μ_t falls, firm relative price increases, firm demand elasticity increases, firm reset price falls. Since monetary shocks and movements in μ_t are small, large real effects occur only if firms' demand elasticity increases a lot when μ_t falls by a little. Parametrically, this requires a large *super-elasticity* of demand—the elasticity of the elasticity of demand. By symmetry, however, this implies that a large decline in μ_{it}, due to a negative idiosyncratic shock, will drastically *decrease* the elasticity of demand. For a firm with a low markup this sharply increases value of a price increase. This latter case approximates the day-to-day workings of the firm: aggregate shocks are small, and the firm most

[37] Technically, such a demand system is distinguished from the CES demand system in that the aggregate price index is a first-order term. The log-linear demand curves derived from CES utility lead to static first order conditions from which the aggregate price drops out. First order conditions under Kimball maintain the aggregate price index.

[38] Studying pass-through in an international setting Gopinath and Itskhoki (2008) and Berger and Vavra (2013) also use a Kimball demand aggregator in a menu cost model. Both papers conclude that having a demand elasticity that is increasing in the firms markup is important for capturing imperfect exchange rate pass-through.

[39] As Nakamura and Steinsson (2010) continue in Section VB, the results of Klenow and Willis (2016) *"cast doubt on strategic complementarity as a source of amplification in menu cost models with idiosyncratic shocks"*

frequently responds to idiosyncratic shocks.[40] As such, increasing the super-elasticity, *ceteris paribus*, makes the profit function more concave, sharply increasing firm level price flexibility (higher frequency of adjustment, smaller size of price changes).

The rejection of these strategic complementarities is then based on three observations. First, to generate large real effects Klenow-Willis must increase the size of shocks from 11% to 28% at a monthly frequency, and double menu costs double as a fraction of revenue, in order to maintain the observed firm level price flexibility.[41] Second, the shape of the demand function implies that firms shut-down production in 15% of months. Third, recent empirical studies by Dossche, Heylen, and den Poel (2010) and Beck and Lein (2015) document low values of ε in grocery store data.

The duopoly model generates a pro-cyclical elasticity of demand at marginal firms that causes large real effects, but with lower menu costs, the same size of shocks, and no shut-downs. How is this so? Lower menu costs as a fraction of profits are due to endogenous price stickiness and coordination around high markups, which I discuss in Section 7. Firms never shut down since the profit function is always positive for $\mu_{it} \in [1, \infty)$. Why are the shocks the same size in both models? After a monetary shock it is true that the fall in an inframarginal competitor's price increases the marginal firm's elasticity of demand, as in the Kimball model. But on a day-to-day basis shocks to its competitor's costs may mean its competitor's markup decreases, increases, or—as it does on average—remains unaffected. In this sense, if we were to draw a firms at random from different markup bins, then the average elasticity of demand faced by a firm should not change as we move left to right across bins. This *average* elasticity of demand is well approximated by the frictionless model's elasticity of demand. Targeting the average markup ensures these are similar for both models, so the required size of shocks is the same.

To highlight this point, Figure 11 shows the profit function of the firm under a Kimball aggregator with a super-elasticity equal to ten, as used in Klenow and Willis.[42] The extra curva-

[40] For completeness: A positive idiosyncratic shock *increases* μ_{it}, the firm's elasticity of demand *increases*, which increases the value of a price *decrease*. In this sense the Kimball structure with a positive super-elasticity is symmetric in increasing the frequency of adjustment in response to both positive and negative shocks.

[41] In a similar exercise Beck and Lein (2015) find that even for (i) low values of the super-elasticity of demand ($\varepsilon = 1.5$), and (ii) highly persistent firm-level productivity, the size of shocks must still double to match the size of price change data.

[42] By way of further comparison, Gopinath and Itskhoki (2008) consider a baseline value of $\varepsilon = 4$ and

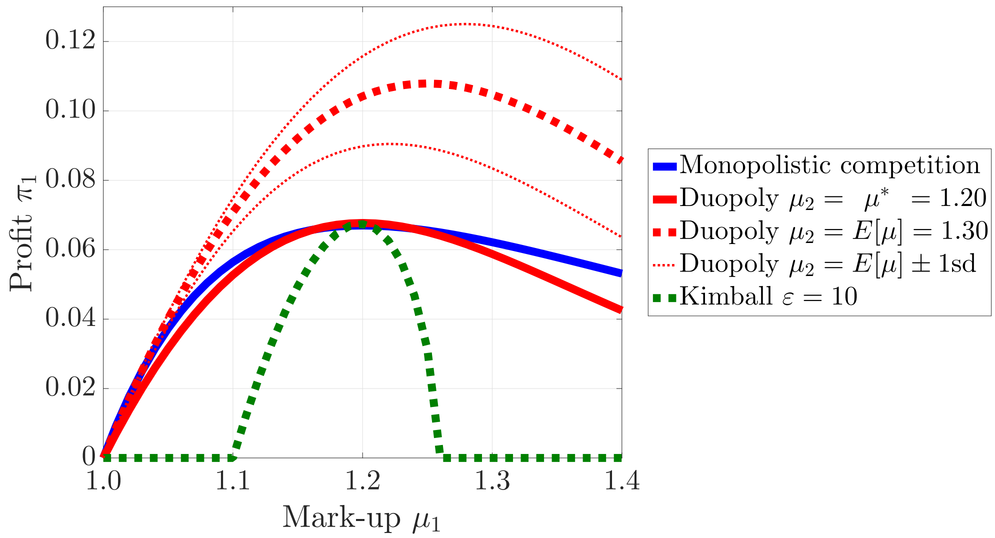

Figure 11: Comparing profit functions across models

Note In all three models compared the frictionless optimal markup is $\mu^* = 1.20$. The elasticities of demand are as in Table 1.

ture in demand shows up as a high degree of extra curvature in profits. The figure also dispels the notion that the duopoly profit function has additional curvature similar to the Kimball profit function. The duopoly model does have excess curvature relative to the monopolistically competitive demand function despite having the same elasticity at the frictionless markup. However the additional curvature is small and is what one would get from a Kimball aggregator with a super-elasticity of $\varepsilon \in [0.3, 0.7]$.[43]

The figure also shows the duopolist's profit function when its competitor's markup is at the average value of 1.31. Comparing this to the monopolistically competitive model with the same frictionless markup, it is clear the first order gains that the MPE policies of the firms attain. If both markups were initially at 1.31, the small gains from the static best response of 1.26 are given by the peak of the profit function minus profits at 1.31. These 'second order gains' are small, requiring only small menu costs to wipe out their value as profitable deviations. This opens up an ability to commit to high markups, with the first order increase in profits approximated by the vertical distances between the red dashed and solid lines.

Berger and Vavra (2013) a value of $\varepsilon = 2.5$.

[43] Beck and Lein (2015) estimate a median super-elasticity of around 1 using European retail goods.

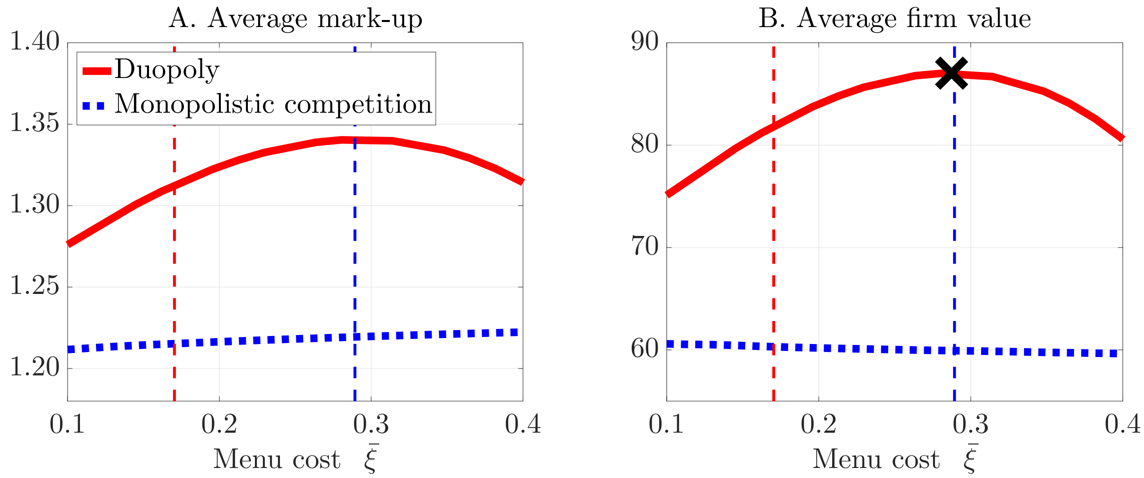

Figure 12: Markups and firm values for large menu costs in the monopolistically competitive and duopoly models

Notes Figures plot the comparative statics of the average markup and average firm value given by Bellman equation (7), with respect to the menu cost $\bar{\xi}$. In each case the other parameters of the model are as in Table 1. Vertical dashed lines give the baseline values of $\bar{\xi}$ from Table 1.

7 Additional results

Two significant more 'microeconomic' results come from studying a dynamic oligopoly model with a fixed cost of changing prices. First, there is a substantial wedge between the frictionless and average markups implying first order losses from nominal rigidities. Second, the duopoly model endogenously generates less flexible prices. This second result has empirical predictions which I test in the following section.

Result 1 - Markups and the welfare cost of nominal rigidity

As noted when discussing Figures 3 and 4, the pricing policies of firms in the duopoly model are able to sustain markups that are higher than the frictionless markup of the model. To quantify this it is helpful to consider again the alternative calibration *Alt III* in which both models have the same frictionless markup. The main result here is that the duopoly model generates an average markup which is 10ppt higher than the frictionless markup, whereas the monopolistically competitive model has a markup that is only 2ppt higher.

Similar to the result in the stylized model of Maskin and Tirole (1988b), menu costs bestow short run commitment to high prices. One firm's high price therefore encourages high prices from its competitor. These *dynamic strategic complementarities* of prices in the presence of adjustment costs have also been studied by Jun and Vives (2004) in a model with no idiosyncratic shocks and convex costs of adjustment. Here I can quantify the wedge between frictionless and average markups in a model that matches the salient features of firm level price adjustment. I also avoid two features of these environments that push towards higher prices: in the first case an exogenous timing assumption, and in the second case a cost of price change that is increasing in the size of the deviation in prices.

Panel A of Figure 12 gives the comparative statics of the average markup with respect to the size of the menu cost. The average markup is sharply increasing in the menu cost in the duopoly model. In the monopolistically competitive model the increase is slight due to the precautionary motive induced by a positive third derivative of the firm's profit function (see Figure E1C): it is relatively more costly to produce large quantities at low prices than small quantities at high prices.

Figure 12B quantifies another stark result of the model: the value of the firm may be increasing in the size of the menu cost. A higher menu cost allows for higher markups but price flexibility falls. In the duopoly model, local to the estimated menu cost, the gains from the former offset losses from the latter. In the monopolistically competitive model the firm would always prefer lower menu costs and firm values are falling in the menu cost. While the monopolistically competitive firm prefers zero menu costs, the duopolist has a value maximizing level of menu costs which is positive. At $\bar{\xi} = 0.29$ the value of the firm is maximized, achieving a value 6 percent higher than at the estimated value of $\bar{\xi} = 0.17$. Figure 7D, drawn for the Calvo model shows that this value maximizing nominal rigidity exists independent of the price change technology.

This implies that in concentrated markets firms may like nominal rigidity in either of its most often modelled forms. Although beyond the scope of this paper, this observation may explain why firms in tight oligopolies might engage in investments that *increase* the cost of price changes. For example, firms may print brochures with prices fixed for some period of time.

A more interesting implication of these results for a macroeconomist is that nominal rigidities induce a first order welfare loss in the duopoly model. Higher markups are higher real prices, and higher real prices mean lower levels of output. The monopolistically competitive model carries the usual second order losses due to price dispersion. These are present and—

due to the calibration—similar in both models. In both the Calvo (Figure 7C) and Menu cost versions of the duopoly model, however, the average markup is substantially higher than the frictionless case. If policies such as higher trend inflation weaken the ability of firms to use menu costs to commit to higher real prices, then such policies can have first order welfare implications. I leave the study of this possibility to future work.[44]

Finally, this result has implications for a common practice in estimating markups in the industrial organization literature. Following Berry et al (1995), a common practice in estimating markups is to first estimate demand elasticities using a static demand system and price and quantity data. The conditions of a static Nash-Bertrand or Nash-Cournot pricing game condition can then be used to infer markups. The counterpart here, would be first estimating η and θ using the firm's demand curve. One could then estimate the markup $\hat{\mu}$ using the expression for the frictionless markup. However the obtained $\hat{\mu}$ would be a downward bias estimate of the true markup which is higher than the frictionless markup due to the dynamic strategic complementarities that are present in a dynamic oligopoly with menu costs. In this sense, getting the model right is necessary to correctly invert markups from demand elasticities.

Result 2 - Lower price flexibility

Table 1 also shows that the duopoly model requires a lower menu cost to deliver the same observed frequency and size of price change as the monopolistically competitive model. In the duopoly model firms with high prices are more reluctant to decrease their prices due to a long-run incentive to maintain a high sectoral markup. Firms with low prices are more reluctant to increase their prices due to a short-run incentive to maintain a high market share. The result is that nominal prices change less often for any given level of the menu cost.

Figure 13 shows that the dominant case is the lower price flexibility at low price firms. This has an additional benefit in bringing the model closer to the data in a way that the monopolistically competitive model struggles. In the monopolistically competitively model, the precautionary motive leads to a lower frequency of adjustment at high priced firms relative to

[44] More broadly these results may distort our understanding of the welfare implications of frictions in macroeconomics. The monopolistically competitive model carries a standard intuitive mapping between frictions and welfare. Moving from right to left in Figure 12, frictions fall, firm value increases and output increases (recall $C = 1/\mu$). In a tight oligopoly there is a range over which lower frictions increase the value of firm but *reduce* output: frictions have a *redistributive* effect.

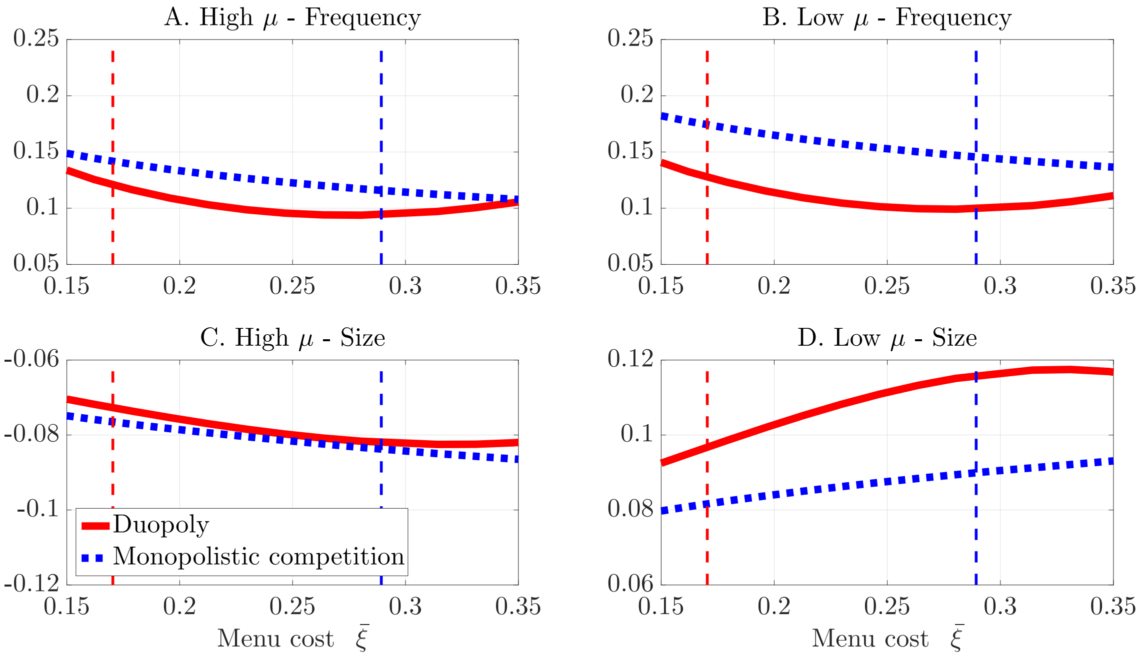

Figure 13: Menu cost $\bar{\xi}$ comparative statics for High vs Low markup firms

low priced firms. The ratio of high priced firm frequency of price adjustment to low priced firm frequency of price adjustment is 0.79 in the monopolistically competitive model. In the duopoly model, the relatively lower incentive to increase price at low priced firms means this ratio is 0.95. In similar data as used in this paper Burstein and Hellwig (2007) document that low and high priced goods have the same frequency of price change (a ratio of 0.97). The monopolistically competitive model is unable to generate this kind of symmetry in adjustment.

Table 2 summarizes this and a number of other results from the comparison of the two models.

8 Price flexibility and market concentration in the data

The second result in the previous section—that duopoly can be a force towards less flexible prices—motivates me to study the relationship between market concentration and price flexibility. I show that there is a systematic relationship between the two, and that this can be viewed as supportive of the predictions drawn from my results. In particular, and consistent with the model, a concentrated market structure leads to endogenously stickier prices. Meanwhile markets that can be characterized by atomistic firms, display more flexible prices.

Moment	M.C. (1)	Duopoly (2)	Ratio* / Diff+ (3)
Average markup	1.22	1.31	0.09^{+}
Standard deviation of consumption	0.13	0.29	2.23^{*}
Cumulative consumption response	2.02	4.36	2.15^{*}
Average firm value	59.9	81.8	1.37^{*}
... at max ξ^{*}	-	87.0	1.06^{*}
Frequency - Low μ	0.146	0.128	-0.018^{+}
Frequency - High μ	0.116	0.121	0.005^{+}
Size - Low μ	0.090	0.097	0.007^{+}
Size - High μ	-0.084	-0.073	-0.011^{+}

Table 2: Summary of statistics

Notes Summary of statistics from monopolistically competitive (column 1) and duopoly model (column 2), at the parameter values given in Table 1. Data points marked with a $*$ ($+$) in column 3 give the ratio (difference) between moments from the duopoly and monopolistically competitive models. The entry of 1.06 for 'Value at max ξ^{*}' is the ratio of the value of the firm in the duopoly model under the value maximizing menu cost to the value under the estimated menu cost.

Motivation from the model A key result of the previous section was that prices are endogenously more rigid when firms act non-atomistically with respect to their sector. This result comes straight from the fact that in the duopoly model, lower menu costs are required to match the empirical frequency of price adjustment. I also noted that the monopolistically competitive model is mathematically identical to a model with a monopolist in each sector, subject to $\eta = \theta$. This gives an intuition for price flexibility under one, two and infinitely many firms: prices are more flexible in the two limiting cases, and less so under duopoly.[45]

What to test? Suppose firms in all markets faced an economic environment determined by the same parameters (ie $\bar{\xi}$ and σ_z are constant across markets). What should we expect as we move from markets with one firm to markets with two firms? There are two off-setting forces. First, the elasticity effect discussed in Section 6.4 would imply that frequency of adjustment would increase. Competing with more firms, any one firms' revenue share is lower, so their

[45] The case of three and four firms, and so on, I leave to future work. I note briefly that the computational difficulty with solving the model with more firms comes not with (i) integrating over more firms actions when computing payoffs, (ii) adding state variables which increases the dimensionality of the value function problem, but with converging on the MPE policy functions which are more awkward to approximate in three or more dimensions.

elasticity of demand is higher.[46] Second, there are the strategic forces studied in this paper. With a few firms, those with high prices have a long-run incentive to not reduce their prices so that a higher sectoral markup is maintained. Low priced firms have a short-run incentive to not adjust as they gain market share. Both lead to less price flexibility. As we consider markets with more and more firms, we might expect this second force to dissipate and the elasticity effect to dominate: firms increasingly behave atomistically and the frequency of price change increases.

This thought experiment leads me to test for a U-shaped (hump-shaped) relationship between frequency (size) of price change and market concentration. Note that increasing price flexibility as firms are added does not suggest that these oligopoly forces are not present, only that they are weaker than the elasticity effect. In this sense the right tail of a U-shape is confounded. However, decreasing price flexibility as firms are added indicates that the oligopoly effect is both present and strong enough to offset the elasticity effect.

Variation in concentration To carry out these tests I return to the IRI data and exploit two separate sources of variation in the concentration of markets. The first uses variation *across states, within product categories*. The second uses variation *across product categories, within states*. Figure 14 provides examples. Panel A describes the time-series of the effective number of firms in the market for Mayonnaise in four different states. Clearly there is very little variation in the time dimension, whereas variation across states is large. Panel B describes the same time-series but for different product categories within the state of New Jersey. Here most of the variation is across products.

What is both striking, useful, and surprising, about this kind of variation in the data is that cases arise where the market for product X may be very concentrated in state A and less in state B, however the market for product Y is more concentrated in B than A. Market concentration is location-good specific. Furthermore, it appears to be an almost permanent feature of markets.

This implies that any systematic relationship between concentration and price flexibility that is consistent across both sources of variation would be very difficult to explain using variation

[46]Figure 8A shows this relationship between elasticity of demand and frequency of price change in the monopolistically competitive model. Appendix **??** describes this relationship in the static frictionless equilibrium of the duopoly model, studying comparative statics with respect to household preference weights for each firm. A higher preference for good one lowers the market share for firm two and increases its elasticity of demand. See discussion in Footnote **??**.

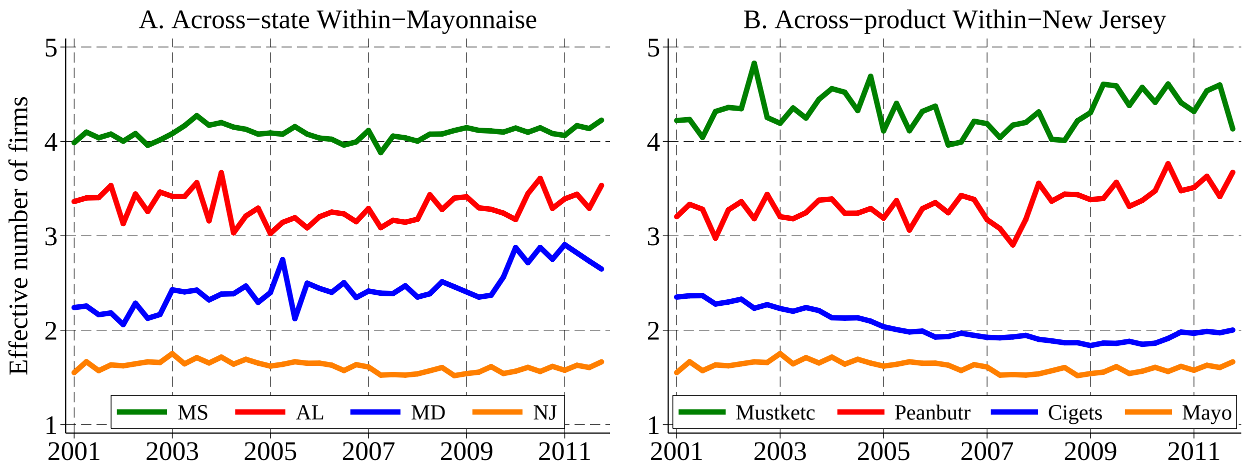

Figure 14: Variation in market concentration

Notes For construction of the *Effective number of firms* measure see the notes to Figure 1. Each series gives effective number of firms for a given product-state market, computed using revenue shares within a quarter.

in menu costs or the stochastic process for costs. This has been the primary approach to modelling variation in price flexibility in structural models (Nakamura and Steinsson (2010), Weber (2014)). Such an explanation would require variation that is neither consistent across goods or locations. This would seem a tall order, compounded by the additional fact that the products in this data are (i) all non-durable goods, (ii) sold in similar stores.

Variation in flexibility Figure 15 describes the variation in price flexibility found in the data. Comparable to Figure I in Nakamura and Steinsson (2010), panel 1A describes heterogeneity in the frequency of price change across product p, state s, quarter t markets. This paper adds to the analysis of heterogeneity in price flexibility by noting that even *within* product groups there is substantial heterogeneity. Panels B and C of each row show the substantial variation found when (B) comparing the same products across states, and (C) comparing different products within states. To quantify this variation I note that the average absolute deviation of frequency of price change from its across-state within-product mean is 0.034, or 29 percent. For absolute size of price change the mean deviation is 0.0098, or 9.4 percent of its mean.[47] These statistics are very similar, but in all cases a little larger when considering across-product within-state

[47] To be precise, let x_{pst} be the price flexibility measure. Then the first statistic is $X_1 = (ST)^{-1}\sum_{s=1}^{S}\sum_{t=1}^{T}\left(x_{pst}-\bar{x}^s_{pt}\right)$, the second statistic is $X_2 = (ST)^{-1}\sum_{s=1}^{S}\sum_{t=1}^{T}\left(x_{pst}-\bar{x}^s_{pt}\right)/\bar{x}^s_{pt}$.

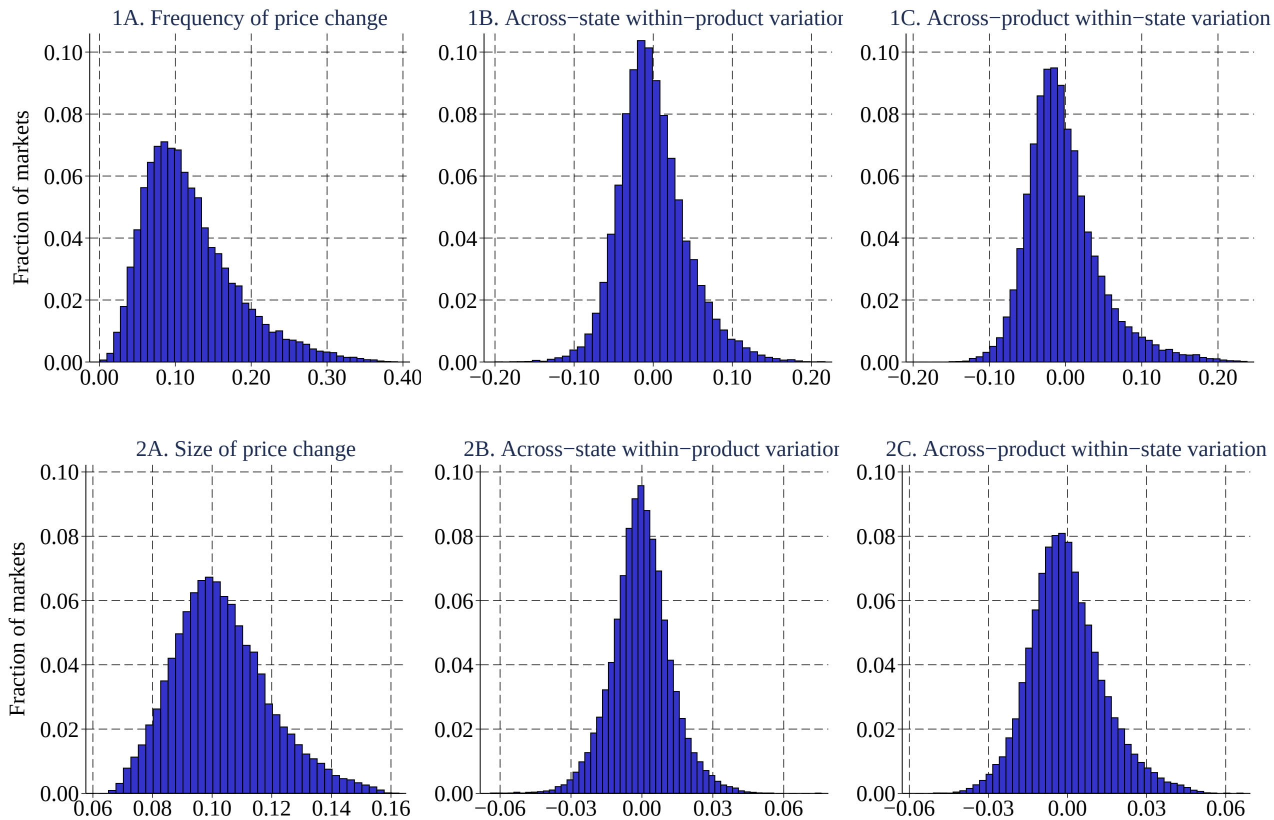

Figure 15: Variation in (1) frequency, (2) absolute log size of price change

Notes The first (second) row of figures refers to the average monthly frequency of price change (log absolute size of price change), y_{pst}, in market pst. In each row the histograms are as follows. **Panel A.** Histogram of y_{pst}. **Panel B.** Histogram of deviations of y_{pst} from its average value across-state within-product average in quarter t: $\bar{y}^{p}_{st}$. **Panel C.** Histogram of deviations of y_{pst} from its average value across-product within-state average in quarter t: $\bar{y}^{s}_{pt}$.

variation.[48] I now quantify the extent to which the variation in price flexibility in panels B and C can be explained using the previously described variation in market concentration.

Estimating equations Let y_{pst} be a measure of market concentration in a product p, state s, quarter t market. Let x_{pst} be a measure of price flexibility, and X_{pst} some other data at the market level. The across-state within-product regression specification is

$$\left(y_{pst} - \bar{y}_{pt}\right) = \alpha_t + \beta\left(x_{pst} - \bar{x}_{pt}\right) + \delta\left(x_{pst} - \bar{x}_{pt}\right)^2 + \gamma X_{pst} + \varepsilon_{pst} \tag{11}$$

[48] Average deviation of frequency is 0.040, or 33 percent. Average deviation of size is 0.015, or 11 percent.

	Across-state w/in product		Across-product w/in state	
	Size (%)	Frequency	Size (%)	Frequency
Eff. number of firms	0.244***	-0.912***	0.201***	-0.900***
	(0.037)	(0.161)	(0.043)	(0.181)
Eff. number of firms^2	-0.048***	0.171***	-0.038***	0.228***
	(0.010)	(0.043)	(0.012)	(0.072)
Observations	32,016	32,016	32,016	32,016
R-squared	0.100	0.106	0.036	0.031
Quarter FE	✓	✓	✓	✓
Rev_{pst} control	✓	✓	✓	✓

Table 3: Regression results - Cross-product regression

Notes Results for the estimation of equation (11) (first two columns) and (12) (last two columns). Data-points in the regression consists of product-quarter-state level observations. **Size** of price change is the product-quarter-state average of monthly log absolute price changes for all products conditional on price change. For example, for each calendar month in 2005:Q2 I compute the average log price change of all shampoo products in New Jersey. I then take the average of these observations. **Freq** is frequency of price change, computed at the same level and is the fraction of goods changing price. Effective number of firms is given by the inverse Herfindahl index h_{pst}^{-1} for market *pst*, where the Herfindahl index is the revenue-share weighted average revenue-share of all firms in the market, $h_{pst} = \sum_{i \in \{pst\}} (rev_{ipst}/rev_{pst})^2$. Errors are clustered at the *ps*-level.

where $\bar{y}_{pt}$ is an across-state weighted mean taken within product p in quarter t. The across-product within-state regression specification is

$$\left(y_{pst} - \bar{y}_{st}\right) = \alpha_t + \beta\left(x_{pst} - \bar{x}_{st}\right) + \delta\left(x_{pst} - \bar{x}_{st}\right)^2 + \gamma X_{pst} + \varepsilon_{pst} \tag{12}$$

where $\bar{y}_{st}$ is a cross-product weighted mean taken within state s in quarter t.

In the main results I consider the effective measure of firms as a measure of market concentration, and frequency and average size of price change as measures of price flexibility. I include one additional control for revenue in the market *pst*. Errors are clustered at the state-product level.

Results from these regressions are given in Table 3. Consistent with the theory, the quadratic terms are negative (positive) in the case of size (frequency) of price changes. Reassuringly, the coefficient estimates are very similar across both regression specifications, despite each using very different sources of variation in the data.[49]

[49] Additional tables in Appendix E show that the results are robust to different specifications. Weighting by the

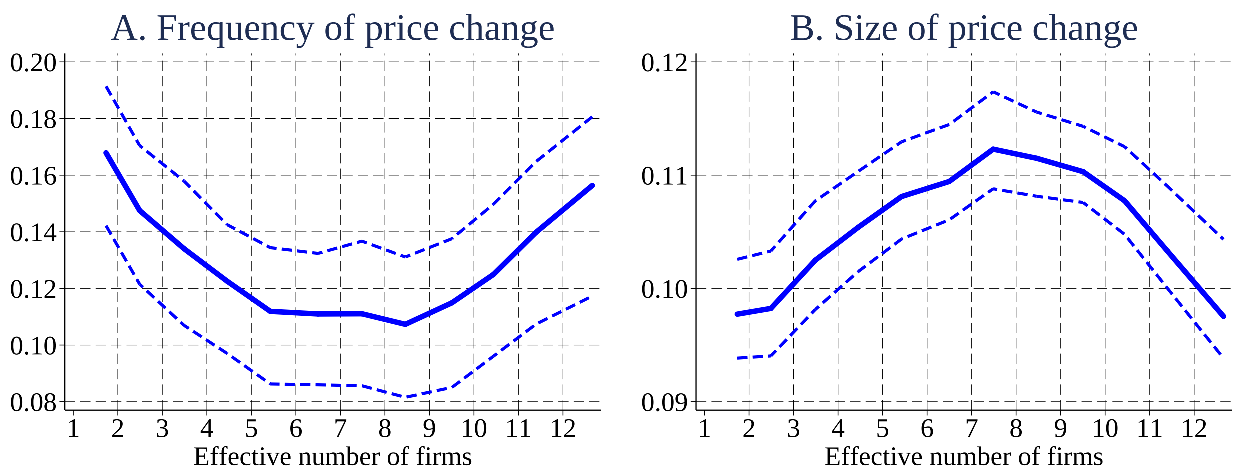

Figure 16: Variation in market concentration

Notes Solid (dashed) lines are medians (25th/75th percentiles) of fitted values from regression (11), where averages for both effective number of firms and the dependent variable are taken within bins of effective number of firms of width one.

Figure 16 displays these results graphically. The solid lines give the average fitted values of frequency and size of price change from the across-state within-product regression (11). Dashed lines give the 25th and 75th percentiles of the fitted values. The model's interpretation of these plots would be that oligopolistic forces are strong, counteracting the elasticity-effect, but weaken at around five equally sized firms. Consistent with the model, price flexibility is similar in markets with very low and very high levels of concentration in which firm behavior may be described as atomistic. These results suggest a promising route for future research in which models with more than two firms per sector can be used to understand when and how these oligopoly forces peak.

9 Extension - Endogneous entry

Results from this extension are currently works in progress.

number of different goods in each market (Table E1) or uniform weights (Table E2) does not affect results. Neither does removing the control for total market revenue (Table E3). Using the revenue share of the largest firm as a measure of concentration results in significant quadratic terms only in the across-state within-product case (Table E4).

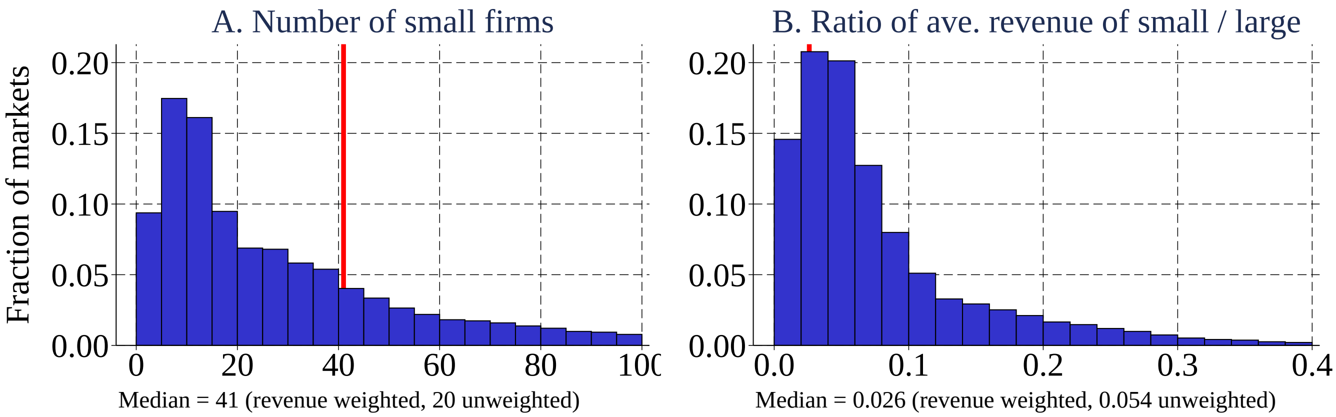

Figure 17: Small and large firms in IRI data

Notes Large firms are defined as the largest two firms in each market by revenue. Small firms are all other firms. For the definition of a market see the notes to Figure 1.

9.1 Competitive fringe with entry and exit

Here I consider an extension of the baseline model designed to capture two key features of the data that may be important for the strength of the oligopoly mechanism. First, there are more than two firms per sector. Second, these other firms are small. Figure 17 describes these facts. Outside of the largest two firms in a market the median number of firms is around 20 and these firms are on average a twentieth of the size of large firms.[50] In this section I will model a fringe of small firms that (i) enter endogenously, (ii) are atomistic and compete monopolistically competitively given the prices of the large firms.

Accommodation vs. Predation There are two clear channels through which adding endogenous entry of a competitive fringe may affect monetary non-neutrality, each pushing in different directions. Consider a positive demand shock. On the one hand, the large firms may respond more aggressively, increasing their prices and accommodating entry. Since demand is high, then new entrants will also post relatively high prices. The *accommodative* behavior of large firms is therefore optimal in that it keeps average prices high. With optimal prices increasing and the price index becoming more flexible due to entry, the response of output is muted. On

[50]Recent work in the industrial organization literature has considered this question restated as *How does the possibility of entry generate competition among incumbents that is high, even when the number of incumbent firms is low?* For example Kokovin, Parenti, Thisse, and Zhelobodko (2015) show that in a one-period model free entry can lead a monopolist to sell at the monopolistically competitive price it would choose in a market that had infinitely many incumbents.

the other hand, if fringe firms produce highly substitutable varieties of the sectoral good, then their markups will on average be lower than that of large firms. Therefore large firms may choke off entry following a demand shock by keeping their prices low. The *predatory* behavior of incumbents keeps prices low, and output increases by more.

Preferences The modifications to the baseline model to accommodate these features are minimal. I assume that preferences over sector j consumption are given by

$$\mathbf{c}_{jt} = \left[\omega^{\frac{1}{\eta}}\left[(z_{1jt}c_{1jt})^{\frac{\eta-1}{\eta}} + (z_{2jt}c_{2jt})^{\frac{\eta-1}{\eta}}\right] + (1-\omega)^{\frac{1}{\eta}}\,\mathbf{c}_{fjt}^{\frac{\eta-1}{\eta}}\right]^{\frac{\eta}{\eta-1}},$$

where ω denotes the preference weight on the two leading firms and $\mathbf{c}_{fjt}$ is the utility of consumption of the goods produced by *fringe* firms. I assume that this is also CES where k indexes a firm, δ_{jt} is the endogenous measure of firms in the fringe, and ρ is the elasticity of substitution between these firms' goods. Preferences and the equilibrium price index are

$$\mathbf{c}_{fjt} = \left[\int_0^{\delta_{jt}} c_{kjt}^{f\,\frac{\rho-1}{\rho}}\,dk\right]^{\frac{\rho}{\rho-1}} \quad , \quad \mathbf{p}_{fjt} = \left[\int_0^{\delta_{jt}} p_{kjt}^{f\;1-\rho}\,dk\right]^{\frac{1}{1-\rho}}.$$

If $\omega = 1$, then the baseline model is obtained.[51]

Fringe firms I assume that fringe firms (i) live for only one period, (ii) face the same production technology as the large firms, (iii) face a fixed cost of entry, and (iii) choose to enter following the realization of incumbent firm prices. The optimal prices of fringe firms are therefore identical and equal to a constant markup over marginal cost, which leads to a simple expression for the fringe price index,

$$p_{kjt}^{f} = \frac{\rho}{\rho-1}W_t \quad , \quad \mathbf{p}_{fjt} = \delta_{jt}^{-\frac{1}{\rho-1}}\frac{\rho}{\rho-1}W_t.$$

[51]For simplicity I have assumed that the household does not have a preference shock for fringe firm's goods. It is trivial to add this.

Variable profits of fringe firms are also identical $\pi^f_{kjt} = \pi_{fjt}$, where

$$\pi_{fjt} = (1-\omega)\left(\frac{p^f_{kjt}}{\mathbf{p}_{fjt}}\right)^{-\rho}\left(\frac{\mathbf{p}_{fjt}}{\mathbf{p}_{jt}}\right)^{-\eta}\left(\frac{\mathbf{p}_{jt}}{P_t}\right)^{-\theta}\left(p^f_{kjt} - W_t\right),$$

$$\pi_{fjt} = (1-\omega)\,\delta_{jt}^{-\frac{\rho-\eta}{\rho-1}}\mathbf{p}_{jt}^{\eta-\theta}P_t^{\theta}\left(\frac{1}{\rho-1}\right)\left(\frac{\rho}{\rho-1}\right)^{-\eta}W_t^{1-\eta}. \tag{13}$$

Entry I assume that fringe firms face a fixed cost $\phi > 0$ of entry. Given an infinite mass of potential entrants, a free-entry condition $\pi_{fjt} = \phi$ determines equilibrium δ_{jt}. To see how, note that δ_{jt} enters the fringe profit in two places. First as δ_{jt} increases, the fringe price level falls making a firm less competitive with respect to the *fringe*. This is the term that appears directly in (13). [52] Second, the sectoral price index is

$$\mathbf{p}_{jt} = \left[\gamma\left[\left(\frac{p_{1jt}}{z_{1jt}}\right)^{1-\eta} + \left(\frac{p_{2jt}}{z_{2jt}}\right)^{1-\eta}\right] + (1-\gamma)\,\delta_{jt}^{\frac{\eta-1}{\rho-1}}p_{fjt}^{1-\eta}\right]^{\frac{1}{1-\eta}}. \tag{14}$$

If $\rho > \eta$, the markups of fringe firms are lower than the large firms. So as δ_{jt} increases the price level falls, making fringe firms less competitive with respect to the *sector*. Both effects decrease profits.

Equilibrium Let $\mathbf{p}\,(p_1, p_2, s, S, \delta)$ give the sectoral price index (14) under the value of δ that solves (13). When deciding on p_i, large firm i takes this function, and the price of its large competitor p_{-i} as given. That is, within each period the static entry game is sub-game perfect, and across periods the two large firms' policies are Markov perfect.

Calibration This extension of the model can be calibrated to accommodate more of the data than the baseline model. The ratio of prices of large to small firms can be used to pin down ρ. The revenue share of the two largest firms pins down ω, conditional on a value of ϕ that normalizes δ to one on average. One could then study whether large firms either accommodate or discourage entry following an increase in the money supply. In the first case weakening the

[52]As the measure of fringe firms increases, the household has an increased ability to substitute, lowering its price index.

response of output, in the second case amplifying it.

10 Conclusion

In this paper I have shown that the competitive structure of markets can be important for the transmission of macroeconomic shocks. In particular, in a quantitative menu cost model of firm level price setting—which aggregates to a monetary business cycle model—I showed that a monopolistically competitive market structure and a duopoly market structure can generate different levels of monetary non-neutrality. Even when calibrated to match the same salient features of price flexibility in the data, the duopoly model generates larger output responses. Following a monetary expansion the incentive for low priced firms to respond to the shock increases less sharply as a lower sectoral price reduces the incentive to adjust. Nominal rigidity plus the ability to time price changes are shown to be crucial in allowing firms to commit to these policies which lower monetary neutrality and increase markups in equilibrium.

More broadly, this paper aims to bridge an inconsistency between data and macroeconomic models that aggregate idiosyncratic firm behavior. Recently, macroeconomic models with heterogeneous firms have been used to answer questions of the following type: Micro-data suggests a friction of type-x at the firm level, does incorporating this friction affect the aggregate dynamics of the economy with respect to aggregate shocks? Examples of such frictions include fixed costs of investment, equity issuance costs, collateral constraints on borrowing, and—in the model studied in this paper—menu costs of price adjustment. These models are used to interpret data that has a key feature: the size distribution is fat tailed.[53] Yet in these models firms are assumed to behave atomistically, regardless of their size. This paper extends the structure of models used to answer these questions to allow for non-atomistic behavior, and found—in the case of nominal rigidities and monetary shocks—that this can be important for aggregate dynamics.

The structure of the model studied in this paper also allows one to study larger set of microeconomic behavior and its implications for macroeconomic outcomes. One could draw motivation from simple, well studied, models of sectoral strategic interaction that may either amplify or moderate macroeconomic shocks. Do firms accumulate excess capacity as a threat against

[53] For example, in the US, around half of all employment is in the largest 0.4 percent of firms.

the expansion of competitors, and if so, does this have implications for the way investment responds to technology shocks? Can monopsony power in labor markets with a few large firms help to explain why wages do not fall sharply in a recession? Returning to the model at hand, one could ask whether changing market concentration over time could help explain the missing inflation of the 2008 Great Recession in the US? Figure E2 shows how concentration has fallen over time when measured at the three digit SIC industry level in Compustat.[54] These and other questions can be asked with modifications of the existing model, while being consistent with a salient feature of the micro-data usually studied through heterogeneous agent models: fat tails of size distributions.

[54]Figure E2 is designed to be only indicative of broad trends. A number of qualifications are relevant. First, three digit industries are coarse. In fact the goods studied in this paper would fall into one three digit SIC category but showed large variation in market concentration. Second, if firms in the sample operate in different geographic markets—a pertinent example is healthcare—then computing concentration measures from national revenue shares is not appropriate. This also applies to industries that are competing domestically with foreign firms (since foreign firm revenue is not included when computing revenue shares), or sell internationally (since foreign and domestic sales can not be distinguished). Third, Compustat includes only large firms. Even with these issues regarding measurement, the common downward trend across all sectors suggests at first-pass that market concentration has fallen.

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Appendix

This Appendix is organized as follows. Section A further describes the IRI data and its treatment. Section B describes the computational methods used to solve the model in Section 3. Section **??** describes the properties of the static Nash equilibrium of the duopoly model with no menu costs. Section E includes additional figures and tables.

A Data description

The data used throughout this paper come from the IRI Symphony data (web-link). Details on this data can be found in the summary paper by Bronnenberg, Kruger, and Mela (2008).[55] The data are at a weekly frequency from 2001 to 2011 and contain revenue and price data at the good level, where a good is defined by a unique barcode number (UPC). Data is collected in over 5,000 stores covering 50 metropolitan areas.[56] For each store, data is recorded for all UPCs within each of 31 different product categories determined by IRI, for example toothpaste, or laundry detergent. The measures that I construct from this data and use in the paper relate to (i) market concentration, (ii) price changes.

To measure market concentration I define a market by product category p, state s and quarter t. I then construct revenue for each firm within market pst by summing revenue for all UPCs within that market. To identify a firm I use the five digits of a good's UPC which uniquely identify the company. For example, the five digits 21000 in the barcode 00012100064595 identify Kraft within a market for Mayonnaise, 48001 identifies Hellman's.

To compute measures of price changes first requires a measure of price. To obtain prices I simply divide revenue by quantity. I compute price change statistics monthly, using observations of prices in the third week of each month. I focus only on regular price changes and deem a price to have been changed in month m if (i) it changes by more than 0.1 percent, considering price changes smaller than this to be due to rounding error from the construction of the price, (ii) it was neither on promotion in month $m-1$, or on promotion in month m. The IRI data

[55] Other recent papers to use this data include Stroebel and Vavra (2014) and Coibion, Gorodnichenko, and Hong (2015).

[56] Details on the identification of stores is removed from the data, replaced with a unique identifying number. Walmart is not included in the data.

includes indicators for whether a good is on promotion and so I use this directly rather than using a sales filter as in Midrigan (2011). This second requirement means I exclude both goods that go on promotion and come off promotion. The frequency of price change in market *pst* is the fraction of goods that change price, where each good has three observations in a quarter, one for each month. The size of price change in market *pst* is the average log change in prices for all regular price changes within market *pst*.

When computing moments for use in the calibration of the model I first take a simple average across states s, and t for each product group p and then take a revenue weighted average over p.

B Computation

First I show that the initially stated Bellman equation (7) corresponds to the re-stated one (10), since the latter is used in computation. Second, I describe the numerical methods used in computing the equilibrium of the model.

Price indices Denote the first firm's markup $\mu_{ij} = \frac{p_{ij}}{z_{ij}W}$. Using this, the sectoral price index $\mathbf{p}_j$ can be written

$$\mathbf{p}_j = \left[\left(\frac{p_{1j}}{z_{1j}}\right)^{1-\eta} + \left(\frac{p_{2j}}{z_{2j}}\right)^{1-\eta}\right]^{\frac{1}{1-\eta}} = W\left[{\mu_{1j}}^{1-\eta} + {\mu_{2j}}^{1-\eta}\right]^{\frac{1}{1-\eta}}$$

Defining the sectoral markup $\mu_j = \mathbf{p}_j/W$, implies $\mu_j = \left[\mu_{1j}^{1-\eta} + \mu_{2j}^{1-\eta}\right]^{\frac{1}{1-\eta}}$. Using the sectoral markup, the aggregate price index P can be written

$$P = \left[\int_0^1 \mathbf{p}_j^{1-\theta} dj\right]^{\frac{1}{1-\theta}} = \left[\int_0^1 \mu_j^{1-\theta} dj\right]^{\frac{1}{1-\theta}} W.$$

Defining the aggregate markup $\mu = P/W$, implies $\mu = \left[\int_0^1 \mu_j^{1-\theta} dj\right]^{\frac{1}{1-\theta}}$.

Profits These expressions for markups can be used to re-write the firm's profit function. Starting with the baseline case

$$\pi_{ij} = z_{ij}^{\eta-1}\left(\frac{p_{ij}}{\mathbf{p}_j}\right)^{-\eta}\left(\frac{\mathbf{p}_j}{P}\right)^{-\theta}\Big(p_{1j} - z_{ij}W\Big)C,$$

and using $C = M/P = 1/\mu$, I obtain

$$\pi_{ij} = \left(\frac{\mu_{ij}}{\mu_j}\right)^{-\eta}\left(\frac{\mu_j}{\mu}\right)^{-\theta}\Big(\mu_{ij} - 1\Big)\frac{W}{\mu} = \tilde{\pi}\Big(\mu_{ij}, \mu_{-ij}\Big)\mu^{\theta-1}W,$$

where the function $\tilde{\pi}$ depends on the aggregate state only indirectly through the policies of each firm within the sector. This step makes clear the use of the technical assumption that z_{ij}

also increases average cost, allowing for an expression for profits only in terms of markups.

Markup dynamics Suppose that a firm sells at a markup of μ_{ij} today. The relevant state tomorrow is the markup that it will sell at tomorrow if it does not change its price $\mu'_{ij} = p_{ij}/z'_{ij}W'$. Replacing p_{ij} with μ_{ij} we can write μ'_{ij} in terms of today's markup and the growth rates of the aggregate wage and idiosyncratic demand

$$\mu'_{ij} = \mu_{ij}\frac{z_{ij}}{z'_{ij}}\frac{W}{W'} = \mu_{ij}\frac{1}{e^{\varepsilon'_{ij}+g'}}.$$

Under the random walk assumption for z_{ij}, we have $z'_{ij}/z_{ij} = \exp\left(\varepsilon'_i\right)$. Under the equilibrium condition that $W = M$ and the stochastic process for money growth we have $W'/W = \exp\left(g'\right)$.

Bellman equation Using these results in the firm's Bellman equation reduces the value of adjustment from (7) to the following, where for clarity I am assuming that the competitor's markup μ_{-i} is fixed

$$V_i^{adj}\left(\mu_i, \mu_{-i}, \mathbf{S}\right) = \max_{\mu'_i}\ \tilde{\pi}\left(\mu'_i, \mu_{-i}\right)\mu(\mathbf{S})^{\theta-1}W(\mathbf{S}) + \mathbb{E}\left[Q(\mathbf{S},\mathbf{S}')V_i\left(\frac{\mu'_i}{e^{\varepsilon_i+g'}}, \frac{\mu'_{-i}}{e^{\varepsilon_{-i}+g'}}, \mathbf{S}'\right)\right].$$

Under the equilibrium discount factor $Q(\mathbf{S},\mathbf{S}') = \beta W(\mathbf{S})/W(\mathbf{S}')$, all values can be normalized by the wage such that $v_i = V_i/W$:

$$v_i^{adj}\left(\mu_i, \mu_{-i}, \mathbf{S}\right) = \max_{\mu'_i}\ \tilde{\pi}\left(\mu_i, \mu_{-i}\right)\mu(\mathbf{S})^{\theta-1} + \beta\mathbb{E}\left[v_i\left(\frac{\mu'_i}{e^{\varepsilon_i+g'}}, \frac{\mu'_{-i}}{e^{\varepsilon_{-i}+g'}}, \mathbf{S}'\right)\right].$$

Replacing the aggregate state $\mathbf{S} = (g, \lambda)$ with that used in the approximation $\mathbf{S} = (g, \mu_{-1})$, we then have the following

$$v_i^{adj}\left(\mu_i, \mu_{-i}, g, \mu_{-1}\right) = \max_{\mu'_i}\ \tilde{\pi}\left(\mu_i, \mu_{-i}\right)\hat{\mu}\left(g, \mu_{-1}\right)^{\theta-1} + \beta\mathbb{E}\left[v_i\left(\frac{\mu'_i}{e^{\varepsilon_i+g'}}, \frac{\mu'_{-i}}{e^{\varepsilon_{-i}+g'}}, g', \hat{\mu}\left(g, \mu_{-1}\right)\right)\right],$$

where $\hat{\mu}$ is given by the assumed log-linear function: $\log\hat{\mu} = \alpha_0 + \alpha_1 g + \alpha_2 \log\mu_{-1}$.

The equilibrium condition requiring the price index be consistent with firm prices has also been restated in terms of markups, which implies the entire equilibrium is now restated in terms of markups. Note that in order to determine *quantities* I need to also simulate paths for M_t and z_{ijt}. To simulate changes in prices it is sufficient to known a path for markups μ_{ijt}, innovations ε_{ijt} and money growth g_t.

To be added

- Solution method for Bellman equation
- Solution method for Krussell-Smith algorithm

C Frictionless Nash equilibrium

Here I verify the statements in the main text regarding (i) the level of the frictionless Nash equilibrium markup, (ii) the properties of the static best response functions. Numerically, these can be verified by examining Figure E1.

Frictionless markup

I state the problem from the perspective of firm one, with the objective function

$$\begin{aligned} \pi_1(\mu_1, \mu_2) &= \mu_1^{-\eta} \mu^{\eta-\theta} (\mu_1 - 1) X, \qquad \text{where} \\ \mu &= \left[\mu_1^{1-\eta} + \mu_2^{1-\eta}\right]^{\frac{1}{1-\eta}}, \end{aligned}$$

and X is due to aggregate variables which the firm takes as given and drop out of its first order condition. In what follows it is useful to note that given the CES structure of demand

$$\frac{\partial \mu}{\partial \mu_1} = \left[\mu_1^{1-\eta} + \mu_2^{1-\eta}\right]^{\frac{1}{1-\eta}-1} \mu_1^{-\eta} = \left(\frac{\mu_1}{\mu}\right)^{-\eta}.$$

We can also write the revenue of the firm $r_1 = p_1 d(p_1, \mathbf{p}(p_1, p_2))$ in terms of markups

$$r_1 = \mu_1^{1-\eta} \mu^{\eta-\theta} W$$

where the wage W is taken as given by both firms. This implies that the revenue share of the firm is

$$s_1 = \frac{r_1}{r_1 + r_2} = \frac{\mu_1^{1-\eta}}{\mu_1^{1-\eta} + \mu_2^{1-\eta}} = \left(\frac{\mu_1}{\mu}\right)^{-\eta} \frac{\mu_1}{\mu} = \frac{\partial \mu}{\partial \mu_1} \frac{\mu_1}{\mu}.$$

Under a CES demand system a firm's revenue share is equal to the elasticity of the sectoral markup with respect to its own price.

The first order condition of the firm's problem is

$$\left[\mu_1^{-\eta} - \eta \mu_1^{-\eta-1}(\mu_1 - 1)\right] \mu^{\eta-\theta} + (\eta - \theta) \mu_1^{-\eta} \mu^{\eta-\theta-1} (\mu_1 - 1) \frac{\partial \mu}{\partial \mu_1} = 0,$$

where the term in square brackets gives the first order condition of a monopolistically compet-

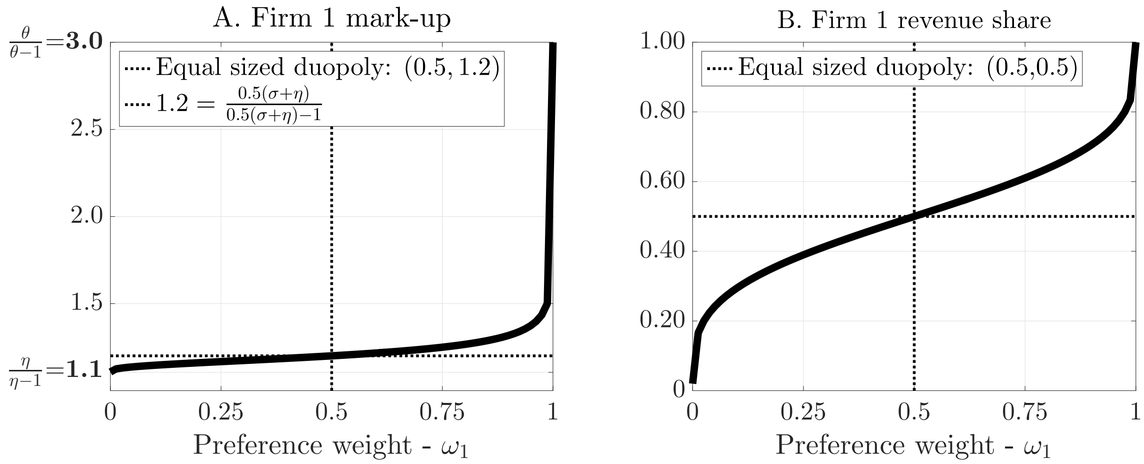

Figure C1: Properties of the static Nash equilibrium of the duopoly model

itive firm facing elasticity of demand η. The second term gives the effect of the firm's markup on the sectoral markup. Since $\eta > \theta$, for any given price of firm two, firm one derives a positive marginal benefit from a higher sectoral price. Substituting in the above result and simplifying we obtain

$$\mu_1 - \eta(\mu_1 - 1) + (\eta - \theta)(\mu_1 - 1)s_1 = 0.$$

Rearranging, the firm's equilibrium markup can be expressed

$$\mu_1 = \frac{s_1\theta + (1 - s_1)\eta}{s_1\theta + (1 - s_1)\eta - 1}.$$

Since the unique equilibrium is symmetric, then $s_1 = s_2 = 0.5$. This implies that markups are consistent with those chosen by a monopolistically competitive firm facing a log-linear demand curve with elasticity of demand $\varepsilon = \frac{1}{2}(\theta + \eta)$.

Figure C1 traces out properties of the static Nash equilibrium for different preferences weights of the household for each firm's good, taking η and θ from Table 1. The parameter ω_1 controls preferences within the sector-level CES function

$$\mathbf{c} = \left[\omega_1 c_1^{\frac{\eta-1}{\eta}} + (1 - \omega_1) c_2^{\frac{\eta-1}{\eta}}\right]^{\frac{\eta}{\eta-1}}.$$

The figure makes clear that in the limit of $\omega_1 = 1$, firm one acts like a monopolist facing a cross-sector elasticity of substitution θ. When $\omega_1 = 0$, the firm behaves monopolistically competitively with respect to its sector facing elasticity of demand η and with a vanishing revenue share. When $\omega = 0.5$ we are in the case studied in this paper with equal revenue shares and a frictionless markup governed by the average of the two elasticities.

Best response functions

The key property of the static best response function $\mu_1^*(\mu_2)$ is that its upwards sloping with a slope less than one. To prove this take firm one's first order condition: $\pi_1^1(\mu_1, \mu_2) = 0$, where the superscript refers to the firm, and the subscript refers to the derivative. By the implicit function theorem, then local to (μ_1^*, μ_2^*), the derivative of $\mu_1^*(\mu_2)$ can be obtained by re-arranging the total derivative of the first order condition

$$\frac{\partial \mu_1^*(\mu_2)}{\partial \mu_2} = -\frac{\pi_{12}^1(\mu_1, \mu_2)}{\pi_{11}^1(\mu_1, \mu_2)}.$$

The second order conditions of the Nash equilibrium require that the principal minors of the Jacobian of the first order conditions alternate in sign,

$$\begin{aligned} \pi_{11}^1(\mu_1^*, \mu_2^*) &< 0, \\ \pi_{11}^1(\mu_1^*, \mu_2^*)\pi_{22}^2(\mu_1^*, \mu_2*) - \pi_{12}^1(\mu_1^*, \mu_2^*)\pi_{21}^2(\mu_1^*, \mu_2^*) &> 0. \end{aligned}$$

By symmetry, the second condition implies that $\left|\pi_{11}^1(\mu_1^*, \mu_2^*)\right| > |\pi_{12}^1(\mu_1^*, \mu_2^*)|$. Combined with the first condition, we have the result that $\partial \mu_1^*(\mu_2)/\partial \mu_2 \in (0, 1)$.

In terms of comparative statics, when strategic complementarities in price setting are larger—that is, π_{ij}^i is large—the slope of the best response function is steeper. In the nested CES model this depends positively on $\eta - \theta$. To see this, combine a slightly simplified version of the first order condition of firm 1,

$$\left[\mu_1^{-\eta} - \eta \mu_1^{-\eta-1}(\mu_1 - 1)\right] + (\eta - \theta)\mu_1^{-\eta}\mu^{-1}(\mu_1 - 1)\frac{\partial \mu}{\partial \mu_1} = 0,$$

with the observation that the cross-partial derivative of the sectoral markup is positive,

$$\frac{\partial^2 \mu}{\partial \mu_1 \partial \mu_2} = \frac{\eta}{\mu}\left(\frac{\mu_1}{\mu}\right)^{-\eta}\left(\frac{\mu_2}{\mu}\right)^{-\eta} > 0.$$

It is clear, then, that when $\eta - \theta$ is large, $\pi^1_{12}(\mu^*_1, \mu^*_2)$ is also larger and the slope of the best response function increases.

D Static game

In this appendix I solve a static price setting game which shows how menu costs can lead to higher prices than obtain in a frictionless setting.

Consider two firms that start with prices $p_1 = p_2 = \bar{p}$. Assume that these prices are greater than the frictionless Nash equilibrium price p^*. The profit function of firm one is $\pi_1(p_1, p_2)$ and the symmetric profit function of firm two is $\pi_2(p_1, p_2)$. These are consistent with the main text[57]

$$\begin{aligned} \pi_1(p_1, p_2) &= p_1^{-\eta} p(p_1, p_2)^{\eta-\theta}(p_1 - 1), \\ p(p_1, p_2) &= \left[p_1^{1-\eta} + p_2^{1-\eta}\right]^{1/1-\eta}. \end{aligned}$$

Let $p^*(p_j)$ denote the symmetric best response function, so that $p^* = p^*(p^*)$.

The rules of the game are that both firms move simultaneously and pay a menu cost ξ to change their price. Consider three types of equilibrium: (i) both firms change their price, (ii) one firm changes its price, (iii) neither firm changes its price.

If both firms change their price, then it must be that the prices chosen are (p_1^*, p_2^*). Given that both firms are changing their prices, then the price chosen by each firm must be a best response to its competitor. This is only satisfied at (p_1^*, p_2^*). If menu costs are zero, then this is the only equilibrium. If menu costs are positive, however, then we also require the following condition to hold

$$\xi \leq \Delta\pi^* = \pi_1\left(p_1^*, p_2^*\right) - \pi_1\left(\bar{p}_1, p_2^*\right). \tag{D1}$$

This states that given that firm two changes its price to p_2^*, then firm one would also change its price to p_1^*. This condition may not hold when either (i) ξ is large, or (ii) $\bar{p}_1$ is close to p^*, since $\pi_1\left(p_1, p_2^*\right)$ is decreasing in p_1 when $p_1 > p^*$.

Now consider requirements for $(\bar{p}_1, \bar{p}_2)$ to be an equilibrium. Clearly if $\xi = \infty$ then this is the only equilibrium. If $\xi < \infty$, then we would also require that

$$\xi \geq \Delta\tilde{\pi} = \pi_1\left(p_1^*(\bar{p}_2), \bar{p}_2\right) - \pi_1\left(\bar{p}_1, \bar{p}_2\right). \tag{D2}$$

[57] In the figures below I use the values of $\eta = 1.5$, $\eta = 10.5$ as in Table 1, such that $p^* = 1.20$.

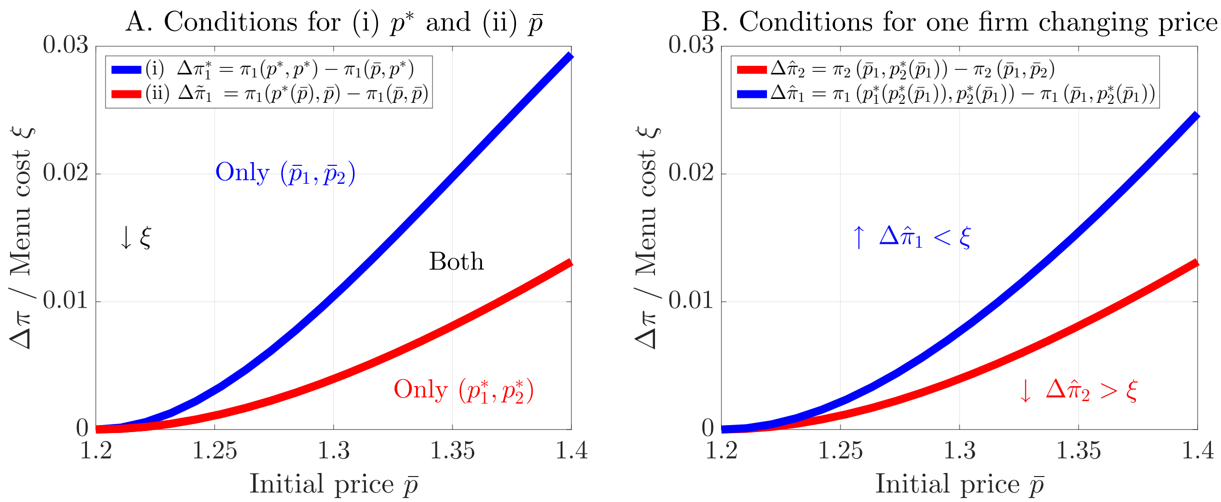

Figure D1: Comparative statics of conditions for the static game

Panel A. plots the left hand side of the conditions (D1) and (D2). **Panel B.** plots the left hand side of the conditions (D3) and (D4) that are required for one firm changing its price to be an equilibrium.

That is, given $\bar{p}_2$, the most profitable deviation for firm one does not increase its value by more than the menu cost.

Figure D1(A) shows that for a given value of $\bar{p}$ (on the x-axis), and a high value of ξ (on the y-axies) we start with only the $\bar{p}$-equilibrium. As ξ decreases, we reach a point where $\Delta\pi^* > \xi$ (given p_1^*, firm two would want to respond with p_2^*), but also $\Delta\tilde{\pi} < \xi$ holds (given $\bar{p}_1$, firm two has no response that increases its value by more than the menu cost). This implies that both equilibria exist. As we further decrease ξ, then $\Delta\tilde{\pi} > \xi$, the no price change equilibrium disappears, and both firms choose p^*.

One firm changing its price is not an equilibrium. If it were, then two conditions must hold. First, firm two must find it profitable to change its price given that firm one's price remains at $\bar{p}$

$$\xi \leq \Delta\hat{\pi}_2 = \pi_2\left(\bar{p}_1, p_2^*(\bar{p}_1)\right) - \pi_2\left(\bar{p}_1, \bar{p}_2\right). \tag{D3}$$

Second, firm one leaving its price fixed must be its best response. The best it can do if it were to change its price would be to choose $p^*(p_2^*(\bar{p}_1))$. Therefore we require that

$$\xi \geq \Delta\hat{\pi}_1 = \pi_1\left(p_1^*(p_2^*(\bar{p}_1)), p_2^*(\bar{p}_1)\right) - \pi_1\left(\bar{p}_1, p_2^*(\bar{p}_1)\right) \leq \xi. \tag{D4}$$

Figure D1(B) shows that these two conditions never hold simultaneously, since $\Delta\hat{\pi}_2 < \Delta\hat{\pi}_1$. If

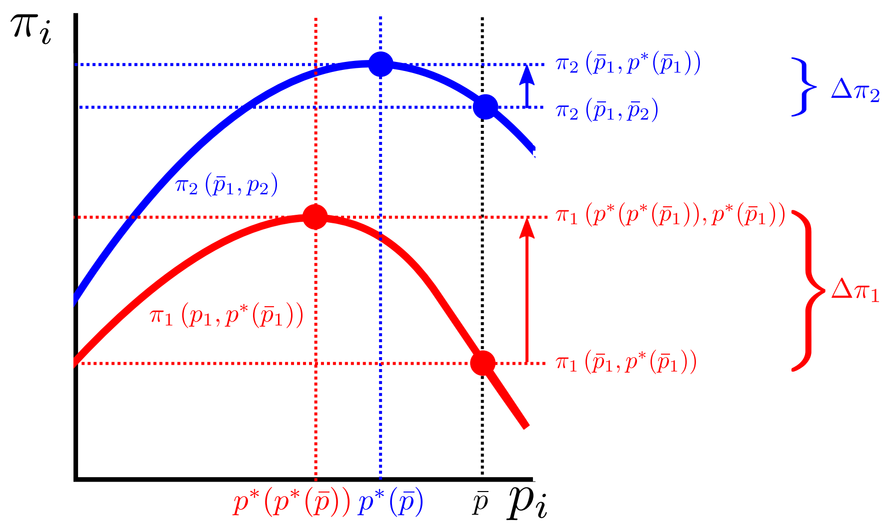

Figure D2: Iterated best responses in static game and their value to firms

firm two chooses its best response to firm one not changing its price, then this greatly increases the profitability of firm one's next iteration of best responses. Any case where firm two finds it profitable to pay ξ and increase its price, firm one would find it profitable to also pay ξ and undercut firm two. Figure D2 depicts graphically these changes in values.

From this static game we observe that for a given menu cost ξ, high prices $\bar{p}$ can be sustained so long as they are not too high. When the initial price is too high, one firm has a profitable deviation, even when they pay the menu cost. If the value of one firm's undercutting strategy exceeds the menu cost, then the value of an iterative undercutting strategy from its competitor also exceeds the menu cost. This leads both firms to change their prices. Once this occurs, only the low frictionless Nash price is achievable. If initial prices are not too high, then the menu cost is enough to wipe out the small value of profitable deviations which make the high priced strategy credible. Quantitatively, the gains from static best responses are second order, requiring small menu costs to wipe them out. The net result is an equilibrium with a higher sectoral markup: a first order term in the firm's profit function.

A helpful way of thinking about the dynamic model is that the firms have an average real price at a $\bar{p}$ in a region where menu costs successfully serve this role. Idiosyncratic shocks force real prices apart, but adjustment strategies keep $\bar{p}$ from becoming too high as to induce strategic undercutting, or too low as to reduce long run firm profitability.

E Additional figures and tables

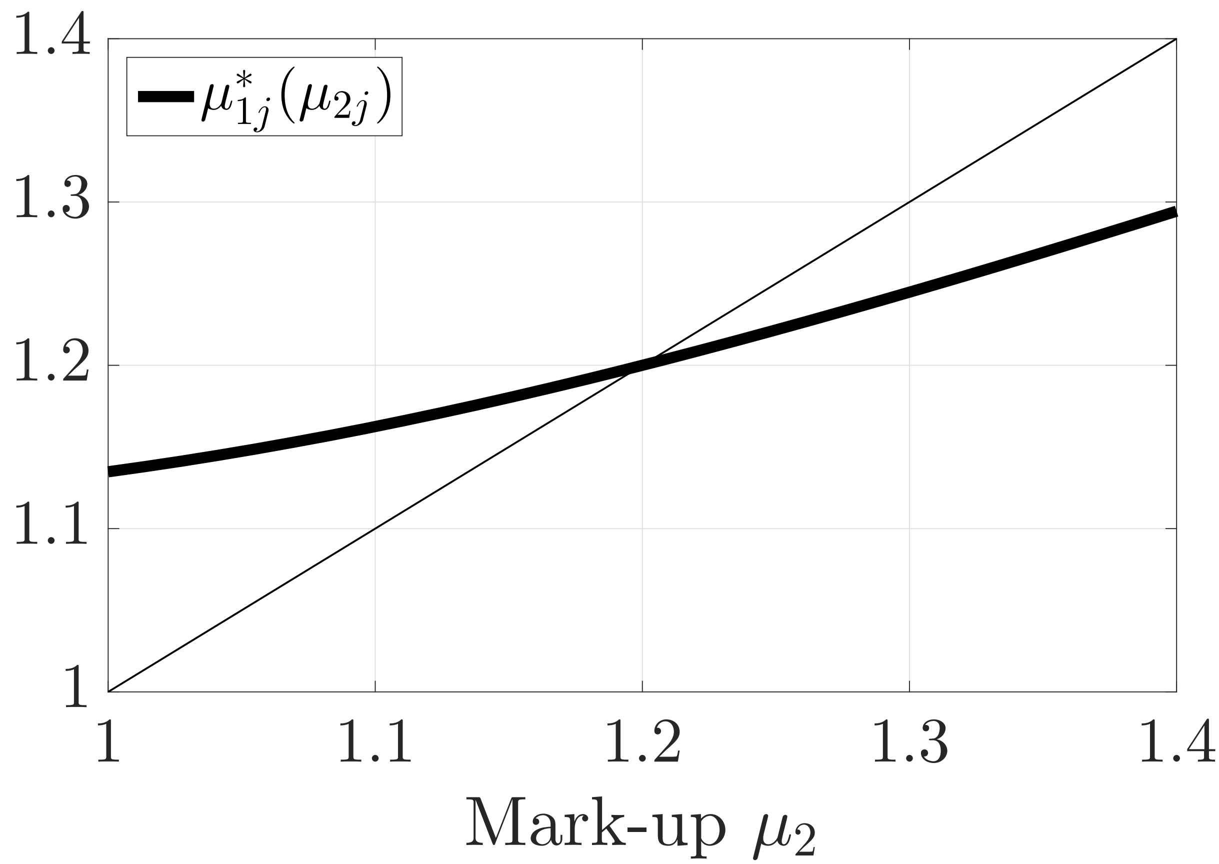

Figure E1: Properties of firm profit functions

Notes Panels A, C, D, display features of the duopoly profit functions under $\theta = 1.5$, $\eta = 10.5$ as in Table 1. Given these parameters, the frictionless Nash-Bertrand markup is 1.20 due to an effective elasticity of demand of $\varepsilon = \frac{1}{2}(\theta + \eta)$ and a symmetric equilibrium. Panel B plots that static best response function $\mu_i^*(\mu_j)$ under $\theta = 1.5$ and different values of η. Higher values of η reduce the Nash equilibrium markup (given by the intersection of the best response with the 45-degree line), and increase the slope of the best response function.

	Across-state w/in product		Across-product w/in state	
	Size (%)	Frequency	Size (%)	Frequency
Eff. number of firms	0.186***	-0.516***	0.147***	-0.661***
	(0.034)	(0.134)	(0.051)	(0.176)
Eff. number of firms^2	-0.024***	0.026	-0.030**	0.177**
	(0.007)	(0.031)	(0.015)	(0.074)
Observations	32,016	32,016	32,016	32,016
R-squared	0.061	0.078	0.009	0.016
Quarter FE	✓	✓	✓	✓
Rev_{pst} control	✓	✓	✓	✓

Table E1: Regression results - Number of goods weighted regression

Notes See notes for Table 3. This table provides results for the same regressions except where the number of goods sold in each market are applied as weights in estimation of equations (11) (first two columns) and (12).

	Across-state w/in product		Across-product w/in state	
	Size (%)	Frequency	Size (%)	Frequency
Eff. number of firms	0.205***	-0.664***	0.138***	-0.667***
	(0.018)	(0.088)	(0.042)	(0.133)
Eff. number of firms^2	-0.018***	0.014	-0.017	0.099
	(0.004)	(0.017)	(0.014)	(0.070)
Observations	32,016	32,016	32,016	32,016
R-squared	0.061	0.078	0.009	0.016
Quarter FE	✓	✓	✓	✓
Rev_{pst} control	✓	✓	✓	✓

Table E2: Regression results - Unweighted regression

Notes See notes for Table 3. This table provides results for the same regressions except where uniform weights are applied in estimation of equations (11) (first two columns) and (12).

	Across-state w/in product		Across-product w/in state	
	Size (%)	Frequency	Size (%)	Frequency
Eff. number of firms	0.244***	-0.956***	0.220***	-0.894***
	(0.038)	(0.181)	(0.043)	(0.181)
Eff. number of firms^2	-0.048***	0.183***	-0.041***	0.227***
	(0.010)	(0.050)	(0.012)	(0.072)
Observations	32,016	32,016	32,016	32,016
R-squared	0.100	0.095	0.028	0.031
Quarter FE	✓	✓	✓	✓
Rev_{pst} control	✗	✗	✗	✗

Table E3: Regression results - No control for revenue

Notes See notes for Table 3. This table provides results for the same regressions except where no additional controls are used in estimating (11) (first two columns) and (12).

	Across-state w/in product		Across-product w/in state	
	Size (%)	Frequency	Size (%)	Frequency
Rev. share top firm	-1.411***	7.727***	-1.436***	6.099***
	(0.428)	(2.015)	(0.392)	(2.286)
Rev. share top firm^2	-9.739***	16.939**	-3.546	13.318
	(1.964)	(7.817)	(3.126)	(17.419)
Observations	32,016	32,016	32,016	32,016
R-squared	0.133	0.107	0.027	0.016
Quarter FE	✓	✓	✓	✓
Rev_{pst} control	✓	✓	✓	✓

Table E4: Regression results - Alternative concentration measure - Revenue share of largest firm

Notes See notes for Table 3. This table provides results for the same regressions except where the revenue share of the largest firm in the market is used as the control variable when estimating (11) (first two columns) and (12).

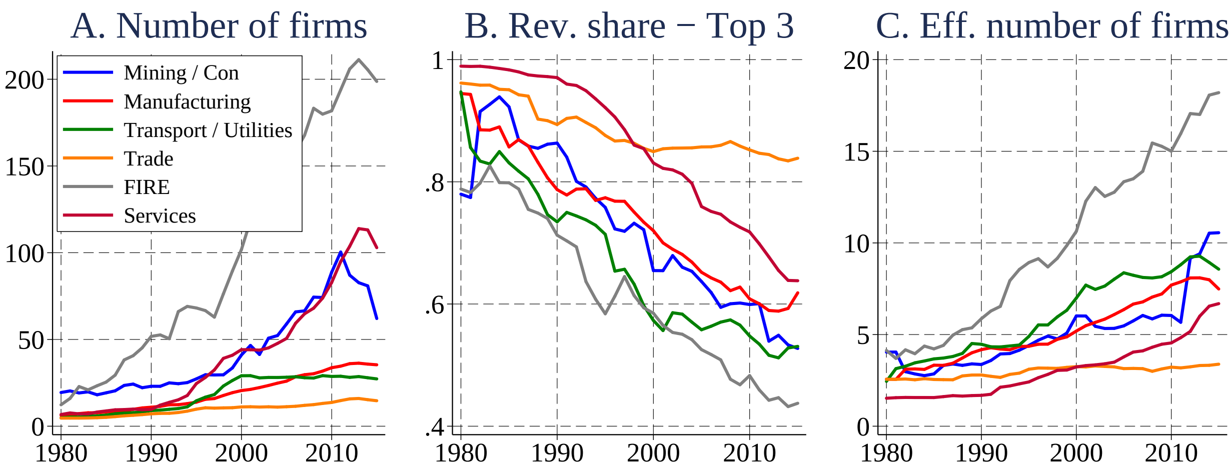

Figure E2: Concentration over time in Compustat data

Notes This figure is constructed using Compustat data from 1980 to 2015. A point in the graph is computed as follows. Take an industry listed in the legend, manufacturing. Within manufacturing there are 87 sub-industries as defined by 3-digit SIC groups. Compute a concentration measure for each of these 87 industries. A point in the graph is the revenue-weighted average of these 87 concentration measures. Revenue is annual and only firms reporting full year revenue are included. For the construction of the effective number of firms measure, see the footnote to Figure 1.